UNIVERSIDADE DE LISBOA

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Evaluation of potential fertilization from Atlantic hydrothermal vents in Calcareous nannoplankton

Kateryna Volochay

Mestrado em Geologia
Especialização em Estratigrafia, Sedimentologia e Paleontologia

Dissertação orientada por:
Prof. Mário Cachão

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Abstract

This study investigates the abundance of coccolithophores in sediment samples collected near hydrothermal vents in the Trans-Atlantic Geotraverse (TAG) zone (26°N), located south of the Azores Archipelago along the Mid-Atlantic Ridge. The primary objective is to assess how proximity to hydrothermal vents influences the distribution of these calcareous nannofossils, with implications for interpreting paleoceanographic conditions associated with such structures.

Sediment samples were collected from the hydrothermal vents at varying distances and prepared using random settling techniques for microscopic analysis. The findings reveal notable vertical variations in coccolithophore abundance, indicating that hydrothermal fluxes may influence their distribution and preservation within marine sediments. The study highlights the potential relationship between hydrothermal activity and coccolithophore abundance. However, limitations such as small sample size and the absence of precise age models constrain definitive conclusions.

Future research should expand sampling efforts, integrate age models, and consider additional environmental variables to elucidate hydrothermal activity's influence on nannoplankton dynamics. This study contributes to understanding deep-sea ecosystems and the paleoceanographic relevance of hydrothermal processes.

Keywords: coccolithophores, hydrothermal vents, TAG zone, Mid-Atlantic Ridge, paleoceanography.

Resumo

Este estudo investiga a influência da atividade hidrotermal na abundância e distribuição de cocolitóforos em sedimentos marinhos da região da Trans-Atlantic Geotraverse (TAG), localizada ao sul do Arquipélago dos Açores, na Dorsal Mesoatlântica. Os cocolitóforos são microalgas calcificantes pertencentes à Divisão Haptophyta, conhecidas por sua importância nos ciclos biogeoquímicos marinhos, especialmente na produção de carbono inorgânico e na formação de sedimentos carbonatados. Além disso, sua ampla distribuição geográfica, sensibilidade a alterações ambientais e presença no registo fóssil como nanofósseis calcários tornam esses organismos indicadores paleoceanográficos valiosos. Compreender como as condições ambientais, especialmente aquelas associadas a fontes hidrotermais, afetam estes nanofósseis calcários pode fornecer informações críticas sobre a dinâmica de ecossistemas marinhos profundos e mudanças paleoceanográficas.

A pesquisa foi conduzida com o objetivo principal de avaliar como a proximidade de fontes hidrotermais pode influenciar a composição e a abundância de cocolitóforos em sedimentos coletados em diferentes locais e profundidades na região TAG. Foram analisados testemunhos de sondagens realizadas em quatro locais: um próximo à fonte hidrotermal, dois a distâncias intermediárias e um mais afastado. A amostragem incidiu sobre diferentes profundidades de cada testemunho, permitindo observar variações verticais (temporais) na composição de espécies e a sua eventual relação com os fluxos hidrotermais. Este estudo tem por objetivo analisar até que ponto os nutrientes, os metais traço (como ferro e manganês) e as condições físicas, como temperatura e disponibilidade de oxigénio, moldam as comunidades de cocolitóforos em ambientes hidrotermais.

Os sedimentos analisados foram obtidos durante expedições científicas da Blue Mining e preparados para análise laboratorial usando a técnica de decantação aleatória. Este método garantiu a uniformidade da distribuição das partículas em lâminas para análise microscópica. Foram examinadas lâminas preparadas a partir de amostras de diferentes profundidades, identificando-se e quantificando-se as espécies presentes. A análise taxonómica seguiu os critérios estabelecidos na plataforma Nannotax3. O cálculo de abundância absoluta (nanólitos por grama) e relativa (percentagens) foram realizados para determinar padrões de distribuição e variabilidade entre os locais e profundidades analisadas.

Os resultados mostram que a atividade hidrotermal parece exercer alguma influência na distribuição de cocolitóforos. Espécies adaptadas a ambientes profundos e ricos em nutrientes, como *Florisphera profunda*, apresentaram concentrações elevadas em locais próximos às fontes hidrotermais. Essa espécie é associada a condições de baixa luminosidade e alta disponibilidade de nutrientes, características comuns em ambientes impactados por fluxos hidrotermais. Por outro lado, *Emiliania huxleyi*, uma espécie de águas superficiais e amplamente distribuída, dominou em áreas mais distantes das fontes, onde predominam condições oligotróficas típicas do oceano aberto.

Foi igualmente documentadas variações verticais nas abundâncias dos taxones identificados. Nos níveis mais profundos foram observadas maiores concentrações de espécies como *F. profunda*, refletindo períodos de maior atividade hidrotermal no passado. Em contraste, as camadas superficiais foram dominadas por *E. huxleyi*, indicando condições recentes mais típicas de ambientes oceânicos, oligotróficos. A presença de espécies como *Gephyrocapsa oceanica* em níveis intermédios sugere respostas a mudanças ambientais episódicas, possivelmente relacionadas a variações na atividade hidrotermal ou fluxos de nutrientes ao longo do tempo. Essas variações verticais destacam a importância da atividade hidrotermal na criação de condições favoráveis à proliferação de espécies específicas e sua preservação nos sedimentos.

Embora os resultados demonstrem existir alguma relação entre a atividade hidrotermal e a composição das comunidades de cocolitóforos, algumas limitações devem ser reconhecidas. O tamanho reduzido da amostra e a ausência de modelos de idade para as sondagens estudadas dificultam a generalização dos resultados e a interpretação temporal das variações observadas. Além disso, a influência de outros fatores ambientais, como correntes oceânicas e processos de sedimentação, não foi completamente investigada e pode ter desempenhado um papel significativo na dinâmica das comunidades de cocolitóforos.

A pesquisa ressalta a relevância das fontes hidrotermais como potenciais impulsionadoras de biodiversidade e moduladoras de processos biogeoquímicos em ambientes marinhos profundos. Os nutrientes e metais traço liberados por essas fontes desempenham um papel essencial na fertilização natural de comunidades marinhas, como os cocolitóforos, influenciando diretamente o ciclo do carbono e a formação de sedimentos carbonatados. No entanto, a crescente exploração de recursos minerais em áreas de fontes hidrotermais, como os depósitos de sulfuretos maciços submarinos, representa uma ameaça potencial a esses ecossistemas. A mineração em mar profundo pode causar perturbações significativas na estrutura das comunidades de cocolitóforos, reduzindo a disponibilidade de nutrientes e alterando a dinâmica dos ecossistemas locais.

Portanto, este estudo contribui não apenas para o avanço do conhecimento sobre a interação entre fontes hidrotermais e cocolitóforos, mas também para a conscientização sobre os impactos ambientais associados à mineração em mar profundo. A compreensão detalhada da relação entre atividade hidrotermal e nanofósseis calcários é crucial para informar políticas públicas e práticas de exploração sustentável. Avaliações de impacto ambiental robustas e a adoção de tecnologias menos invasivas são fundamentais para equilibrar o aproveitamento econômico dos recursos minerais com a preservação da biodiversidade marinha.

Futuros estudos devem focar em ampliar a amostragem geográfica e temporal, incluindo análises isotópicas e geoquímicas para aprofundar o entendimento das interações ecológicas em sistemas hidrotermais. Além disso, investigações sobre as adaptações genéticas dos cocolitóforos a ambientes

hidrotermais poderiam fornecer novas perspetivas sobre a resiliência desses organismos às mudanças ambientais. Estudos de modelagem que simulem os impactos potenciais da mineração em mar profundo também são essenciais para prever cenários futuros e mitigar riscos para os ecossistemas marinhos.

Com base nos resultados obtidos, este estudo reforça a importância de considerar os impactos ecológicos das fontes hidrotermais e da exploração mineral no planejamento de políticas de conservação e desenvolvimento sustentável. A zona TAG, como um laboratório natural para a investigação da interação entre processos hidrotermais e ecossistemas marinhos, oferece uma oportunidade única para compreender melhor as complexas relações que moldam a biodiversidade e os ciclos biogeoquímicos em áreas de alto valor ecológico e econômico.

Palavras-chave: cocolitóforos, fontes hidrotermais, zona TAG, Dorsal Mesoatlântica, paleoceanografia.

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Acronyms

$CaCO_3$	Calcium Carbonate
CH_4	Methane
CO_2	Carbon Dioxide
DIC	Dissolved Inorganic Carbon
DMS	Dimethyl Sulfide
Fe	Iron
GC	Gravity Core
H_2S	Hydrogen Sulfide
JC	Research Cruise Identifier (e.g., JC 138/52 GC)
Na_2CO_3	Sodium Carbonate
$NaHCO_3$	Sodium Bicarbonate
Nannotax3	Online Taxonomic Guide to Extant Coccolithophore Taxa (Young et al., 2021)
SMS	Seafloor Massive Sulfides
TAG	Trans-Atlantic Geotraverse

Objectives

This thesis investigates the influence of hydrothermal vent systems on marine ecosystems, with a particular emphasis on their interactions with microorganisms such as calcareous nannoplankton. By examining these interactions, the study aims to enhance our understanding of how these ecosystems respond to natural mineral influxes and assess their resilience and adaptation implications.

The research is based on sediment samples collected from four distinct locations near hydrothermal vents: one site close to the vent, two at intermediate distances, and one farther away, with samples taken at various depths within each location. This sampling strategy allows for a detailed analysis of how proximity to hydrothermal vents and depth gradients influences the abundance of nannoplankton and the composition of predominant species. The study seeks to determine whether hydrothermal vent activity plays a role in modulating nannoplankton populations and driving changes in species dominance.

A key objective is to analyse how calcareous nannoplankton populations and community structure have responded to natural hydrothermal inputs and to use this understanding to draw parallels with the potential impacts of modern human activities, such as deep-sea mining. By examining the quantitative (abundance) and qualitative (species composition) aspects of calcareous nannofossil variations, the study aims to evaluate how such operations might affect these microorganisms and the broader marine ecosystems they support.

An essential aspect of this research is assessing the feasibility of exploring and exploiting mineral-rich environments in the deep sea while minimising ecological disruption. Understanding the influence of hydrothermal vent activity on the number and types of calcareous nannoplankton is crucial for balancing the benefits of deep-sea mining with preserving biodiversity and ecological integrity in these sensitive habitats.

Additionally, this thesis contributes to addressing challenges related to the Blue Mining project, an initiative focused on developing sustainable methods for deep-sea mining, particularly in Europe’s mineral-rich waters. By providing insights into the ecological implications of hydrothermal activity, this research aims to support strategies that mitigate environmental risks and promote the sustainable use of deep-sea resources.

Through these efforts, this thesis seeks to lay a foundation for future advancements in sustainable deep-sea resource utilisation while deepening our understanding of the relationships between hydrothermal vent systems, nannoplankton abundance, species composition, and broader marine ecosystems. It emphasises the importance of informed decision-making in deep-sea mining activities to protect these vital ecosystems.

1. Introduction

The increasing global demand for essential minerals has driven exploration into previously inaccessible environments, such as the deep sea. As terrestrial reserves diminish and extraction technologies advance, the ocean floor—particularly hydrothermal vent systems—has become a prime target for mineral exploration (Van Dover, 2011). Hydrothermal vents discharge substantial quantities of metals, including iron, copper, and zinc, into the surrounding seawater, forming polymetallic sulfide deposits with significant industrial potential (Hannington et al., 2011). However, the environmental implications of deep-sea mining remain a significant concern, as these ecosystems play vital roles in global biogeochemical cycles and host unique biological communities.

One of the key biological components of marine biogeochemical cycling is coccolithophores, which are unicellular calcifying microalgae that contribute to carbon sequestration by producing calcareous platelets known as coccoliths. These structures settle into marine sediments, forming a crucial archive for paleoceanographic reconstruction (Bown, 1998). Coccolithophore populations are susceptible to environmental changes, including nutrient availability, temperature, and pH variations. Given that hydrothermal vents are important sources of micronutrients, particularly iron, their influence on coccolithophore abundance and calcification dynamics remains an open question (Boyd et al., 2000).

Recent studies by Guerreiro et al. (2017, 2023, 2024) have demonstrated that environmental factors such as thermocline depth, Amazon River input, and Saharan dust deposition influence coccolithophore fluxes. Notably, Guerreiro et al. (2024) highlighted the role of Saharan dust in stimulating coccolithophore productivity and enhancing the biological carbon pump, providing insights into how nutrient inputs shape marine ecosystems across spatial and temporal scales. These findings underscore the need to investigate the impact of hydrothermal activity as an additional driver of coccolithophore dynamics.

This study focuses on the TAG Hydrothermal Field, a well-studied hydrothermal vent system located on the Mid-Atlantic Ridge at approximately 26°N. The TAG field is characterised by active and inactive sulfide mounds, where hydrothermal fluids enriched in metals such as iron (Fe), copper (Cu), and zinc (Zn) interact with deep-sea sediments (Scott et al., 1974, 1978; Chiba et al., 2002; Dutrieux et al., 2023). In addition to essential micronutrients, TAG hydrothermal fluids contain potentially toxic metals such as cadmium (Cd), arsenic (As), and lead (Pb), which may have biological consequences for marine microorganisms, including coccolithophores (Milinovic et al., 2020). Understanding how these hydrothermal-derived elements influence coccolithophore communities is crucial for assessing hydrothermal activity's broader ecological and biogeochemical impacts.

Thus, this study examines hydrothermal vent systems' influence on coccolithophore abundance and species composition, considering the implications for paleoceanographic reconstructions and marine ecosystem resilience. By integrating geochemical and biological perspectives, this research contributes to a more comprehensive understanding of deep-sea processes and informs discussions on the sustainable exploration of hydrothermal mineral resources.

1.1 Coccolithophores: Key Contributors to Marine Ecosystems and Biogeochemical Cycles

Coccolithophores are unicellular calcifying microalgae belonging to the class Prymnesiophyceae. They are essential to marine ecosystems and biogeochemical cycles. Their calcareous platelets, or coccoliths, contribute to marine sediments and have been preserved in the fossil record since the Triassic period (Bown, 1998). Coccolithophores are crucial primary producers, playing a significant role in carbon cycling, as they can both fix atmospheric CO_2 through photosynthesis and aid in the carbonate counter-pump via calcification (Rost & Riebesell, 2004).

Impact of Hydrothermal Vent Nutrients on Coccolithophore Productivity

Hydrothermal vent systems, such as those in the Atlantic Ocean, release trace metals into the water column, potentially serving as natural fertilisers for phytoplankton, including coccolithophores. Iron (Fe), manganese (Mn), and zinc (Zn) are vital for photosynthetic enzymes and cellular metabolism in coccolithophores (Boyd et al., 2000). These metals in hydrothermal plumes can mitigate nutrient limitations, promoting coccolithophore growth and possibly enhancing calcification rates (Guerreiro et al., 2024).

The fertilisation effect of hydrothermal vents on coccolithophores may manifest in:

- Enhanced Primary Production – Increased Fe, Mn, and Zn availability from vent plumes could stimulate coccolithophore growth, particularly in nutrient-poor Atlantic regions. This could increase calcification rates, impacting oceanic carbon cycling (Schulz et al., 2004).
- Changes in Species Composition – Hydrothermal input may favor opportunistic coccolithophore species. For example, *Emiliania huxleyi* and *Gephyrocapsa oceanica* respond positively to iron fertilisation, which has been observed in Saharan dust deposition events (Guerreiro et al., 2024). A similar response is expected near hydrothermal vent-influenced waters.
- Paleoceanographic Significance – Variations in coccolithophore assemblages due to hydrothermal nutrient input may leave distinct signatures in marine sediments, helping reconstruct past oceanic conditions and natural fertilisation events (Winter & Siesser, 1994).

Toxic Trace Metals and Their Effects on Coccolithophores

Although trace metals are vital for coccolithophore productivity, some toxic heavy metals found in hydrothermal vent fluids—such as copper (Cu), cadmium (Cd), and lead (Pb)—can negatively impact coccolithophore physiology. Research has shown that elevated concentrations of these metals can alter coccolith morphology, reduce growth rates, and disrupt calcification.

- Copper (Cu) and Zinc (Zn):

  Emiliania huxleyi exhibits high resilience to elevated Cu and Zn concentrations, likely due to its ability to regulate metal uptake (Faucher et al., 2017).

  Calcidiscus leptoporus tolerates moderate heavy metal exposure but produces smaller coccoliths at high metal concentrations, indicating stress responses.

  Gephyrocapsa oceanica generally maintains its size and structure but decreases its growth rate when trace metal concentrations exceed threshold levels.
- Cadmium (Cd) and Lead (Pb):

  High Cd and Pb levels can disrupt cellular metabolism and reduce calcification efficiency in multiple coccolithophore species (Schulz et al., 2004).

  Morphological alterations in coccoliths, including deformations and irregular growth, have been reported under excessive Cd exposure.

Balancing Nutrient Benefits and Metal Toxicity

Hydrothermal vents provide essential micronutrients and potentially harmful metals, creating a complex interaction that influences coccolithophore community structures. The impact of hydrothermal activity on coccolithophore abundance and morphology depends on metal bioavailability, species-specific tolerance thresholds, and local oceanographic conditions.

- In iron-limited waters, the fertilisation effect may outweigh toxicity, favoring growth-enhancing responses.
- In regions with high concentrations of Cu and Cd, sensitive species may decline, while more tolerant species (e.g., *Emiliania huxleyi*) may dominate.

Understanding these species-specific responses is critical for predicting ecosystem shifts due to natural hydrothermal activity and anthropogenic disturbances such as deep-sea mining.

Coccolithophores are highly responsive to trace metal availability, making them key indicators of hydrothermal vent influences on marine ecosystems. While vent plumes may act as natural fertilisers, toxic metal exposure could alter species composition and calcification efficiency. The extent of these effects will depend on metal concentrations, biological tolerance levels, and ocean circulation patterns. Further research is needed to explore the long-term implications of hydrothermal activity on coccolithophore populations and biogeochemical cycles, particularly in regions targeted for deep-sea mining.

1.2 Hydrothermal Vents: Potential Fertilization of Calcareous Nannoplankton

Hydrothermal vents are key geological and biological systems that shape deep-sea ecosystems and global biogeochemical cycles. These vents form along tectonic plate boundaries, such as mid-ocean ridges, back-arc basins, and volcanic arcs, where seawater interacts with magma beneath the ocean floor (Kelley et al., 2002). The plumes they release are rich in trace metals, including iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu), which can significantly influence marine productivity. Among the many marine organisms affected, coccolithophores, a major group of calcareous nannoplankton, are exceptionally responsive to hydrothermal-derived nutrients. The potential fertilisation effects of hydrothermal vents on these primary producers underscore their role in carbon cycling, sedimentation, and marine ecosystem regulation (Boyd et al., 2000).

Formation and Nutrient Enrichment

Hydrothermal vents are formed when seawater penetrates the oceanic crust, heats up near magma chambers, and dissolves metals and gases from the surrounding rocks. When this superheated, metal-rich fluid is expelled at the seafloor, it interacts with cold seawater, causing minerals to precipitate and resulting in the formation of black smokers and white smokers—chimneys made up of metal sulfides and carbonates (Tivey, 2007). These vent plumes can disperse trace metals such as Fe, Mn, and Zn over considerable distances, affecting nutrient availability in nutrient-poor marine environments (Boyle et al., 2005). In the Atlantic Ocean, hydrothermal vent systems like the TAG Hydrothermal Field contribute significantly to regional iron fertilisation, potentially aiding phytoplankton growth, including coccolithophores (Dutrieux et al., 2023).

Biological Significance: Hydrothermal Trace Metals as Fertilizers

The iron-enriched waters of hydrothermal vents may act as natural fertilisers for coccolithophores, which require trace metals for photosynthesis and calcification (Schulz et al., 2004). Since Fe is a limiting nutrient in many parts of the ocean, hydrothermal iron input could stimulate coccolithophore growth, potentially enhancing calcification rates and organic carbon export (Boyd et al., 2000).

Species Composition and Response to Hydrothermal Inputs

The nutrient dynamics of hydrothermal plumes can influence the structure of the coccolithophore community by promoting the growth of opportunistic species. Like the iron-fertilization effects of Saharan dust (Guerreiro et al., 2024), hydrothermal plumes may encourage the blooms of Emiliania huxleyi and Gephyrocapsa oceanica, both of which thrive under high-nutrient conditions. Such shifts in species dominance have potential implications for biogeochemical cycling and paleoceanographic reconstructions (Winter & Siesser, 1994).

However, while moderate trace metal concentrations can stimulate growth, excessive exposure to certain toxic metals—such as copper (Cu) and cadmium (Cd)—can inhibit calcification and alter coccolith morphology (Faucher et al., 2017). Species-specific responses to metal toxicity include:

- *Emiliania huxleyi* – Shows high resilience to Cu and Zn, allowing it to dominate nutrient-rich environments.
- *Calcidiscus leptoporus* – Tolerates moderate heavy metal concentrations but produces smaller coccoliths at high metal levels, indicating stress adaptation.
- *Gephyrocapsa oceanica* – Tends to maintain normal growth unless trace metal concentrations become excessively high.

Ecological and Biogeochemical Implications

Carbon Cycling and Sedimentation

Coccolithophores contribute to biological and carbonate pumps, sequestering carbon through photosynthesis while simultaneously releasing CO_2 through calcification (Rost & Riebesell, 2004). If hydrothermal vents increase coccolithophore productivity, this could enhance carbon export, leading to more significant sediment deposition of coccolith-rich material (Balch et al., 2011).

Trace Metal Dispersion and Bioavailability

The impact of hydrothermal vent-derived metals depends on their bioavailability and dispersion patterns in the water column. Ocean currents, mixing rates, and redox conditions influence how much Fe, and other metals reach phytoplankton populations (Boyle et al., 2005). If trace metals remain bioavailable, they could support primary producers; however, their fertilisation potential may be limited if they precipitate too quickly.

Potential Risks and Adaptations to Hydrothermal Environments

Adaptations of Hydrothermal Vent Communities

Deep-sea vent organisms exhibit unique adaptations to survive in extreme environments, such as:

- Hydrogen Sulfide Utilization – Chemosynthetic bacteria oxidise H_2S to produce energy, forming the base of vent food webs (Childress & Fisher, 1992).
- Heavy Metal Tolerance – Vent organisms, including shrimp and crabs, have evolved metal detoxification mechanisms to survive in metal-rich environments (Desbruyères et al., 2006).
- Thermal Adaptations – Some microbes and invertebrates can survive in temperature gradients from near freezing to over 300°C (Van Dover, 2000).

Although coccolithophores do not inhabit vent ecosystems directly, the nutrient-rich plumes from vents may enhance their productivity in surrounding waters.

Deep-Sea Mining and Conservation Considerations

While hydrothermal vents provide natural fertilisation, they are also targets for deep-sea mining, raising concerns about potential disruptions to nutrient cycling. Mining seafloor massive sulfide (SMS) deposits could alter trace metal fluxes, potentially reducing the availability of Fe and Mn for primary producers like coccolithophores (Van Dover et al., 2018).

Hydrothermal vents represent a natural source of trace metals, influencing primary marine production and carbon cycling. While moderate trace metal inputs may boost coccolithophore productivity, excessive toxic metal exposure can adversely affect species composition and calcification. The long-term impacts of hydrothermal nutrient input on coccolithophore populations remain an area of active research, particularly in deep-sea mining and climate change.

Hydrothermal vents are dynamic geological and biological systems that shape deep-sea ecosystems and influence oceanic biogeochemical cycles. These systems form where seawater interacts with magma beneath the ocean floor, typically along tectonic plate boundaries, including mid-ocean ridges, back-arc basins, and volcanic arcs (Kelley et al., 2002). The nutrient-rich plumes released by hydrothermal vents may provide critical trace elements, such as iron and manganese, which could act as natural fertilisers for calcareous nannoplankton, including coccolithophores. This potential fertilisation highlights the vents' importance as mineral resources and regulators of marine ecosystem dynamics and carbon cycling.

Formation and Nutrient Enrichment

Hydrothermal vents form through the interaction of seawater with magma. Water penetrates the Earth's crust through fractures and faults, descending toward magma chambers where it is heated to temperatures exceeding 400°C (Van Dover, 2000). The water dissolves minerals and gases, including iron, copper, zinc, sulfur, and hydrogen sulfide, as it interacts with the surrounding rocks (German & Von Damm, 2003). The nutrient-enriched fluid rises to the seafloor, where it is expelled through vent openings, creating plumes laden with dissolved trace elements.

As the superheated fluid mixes with cold seawater, rapid cooling causes dissolved minerals to precipitate, forming characteristic vent structures such as "black smokers" and "white smokers," composed primarily of metal sulfides and carbonates (Tivey, 2007). These plumes can disperse trace metals like iron and manganese over large areas, providing essential nutrients to marine ecosystems (Boyle et al., 2005). This dispersal is particularly significant in regions where micronutrient availability limits primary productivity, such as the open ocean.

Biological Significance and Potential Fertilization of Nannoplankton

Hydrothermal vents host diverse ecosystems sustained by chemosynthesis rather than sunlight. Microorganisms, such as chemosynthetic bacteria and archaea, derive energy from reduced compounds in vent fluid, such as hydrogen sulfide (H_2S), methane (CH_4), and iron (Fe), forming the base of the vent food web (Jannasch & Mottl, 1985). While these organisms dominate vent ecosystems, the plumes emitted by vents can influence biological activity beyond their immediate vicinity, particularly in the pelagic zone.

Trace Metals as Fertilizers for Coccolithophores

The iron-rich plumes from hydrothermal vents are particularly relevant for coccolithophores, which require iron and other micronutrients for growth and calcification. Iron is a cofactor in photosynthetic enzymes and is essential for forming organic and inorganic carbon structures. Increased iron availability near hydrothermal vents could stimulate coccolithophore productivity, potentially leading to enhanced calcification rates and more significant contributions to the marine carbon cycle.

Species Composition and Distribution

The nutrient enrichment from hydrothermal vent plumes may also influence the composition of coccolithophore communities. Opportunistic species like *Emiliania huxleyi* and *Gephyrocapsa oceanica*, known to thrive in nutrient-rich conditions (Guerreiro et al., 2024), could dominate in vent-influenced areas. This shift in species composition could have implications for sedimentary records and paleoceanographic reconstructions.

Ecological and Biogeochemical Impacts

Hydrothermal vents play a vital role in oceanic nutrient cycling and carbon sequestration. The trace metals released by vent plumes contribute to the ocean's dissolved iron pool, which supports primary producers like coccolithophores in nutrient-limited regions. This interaction highlights the vents' indirect influence on global biogeochemical cycles, including the biological pump and carbonate counter-pump.

Carbon Cycling and Sedimentation

Coccolithophores contribute to the biological pump by exporting organic carbon to the deep ocean and the carbonate counter-pump by producing calcium carbonate (Rost & Riebesell, 2004). Enhanced growth and calcification stimulated by hydrothermal fertilisation could increase the deposition of coccoliths in marine sediments, potentially sequestering carbon over geological timescales.

Trace Metal Dispersion

The dispersal of trace metals such as iron and manganese from hydrothermal vents extends their ecological impact beyond the vent site. These metals are critical for marine primary productivity and could enhance the resilience of pelagic ecosystems to nutrient limitations. However, this fertilisation effect depends on the dispersion and bioavailability of vent-derived nutrients, which vary with ocean currents and mixing processes (Boyle et al., 2005).

Adaptations of Vent Communities

The extreme conditions near hydrothermal vents—high pressure, temperature gradients, and chemical toxicity—have driven remarkable adaptations among vent organisms. These adaptations include:

- Utilization of Hydrogen Sulfide: Chemosynthetic bacteria and their symbionts can oxidise H_2S to produce energy, forming the foundation of vent ecosystems (Childress & Fisher, 1992).
- Tolerance to Heavy Metals: Vent-dwelling organisms, such as crabs and shrimp, possess physiological mechanisms to tolerate high concentrations of metals.
- Thermal Adaptations: Many vent organisms can survive in temperature gradients ranging from near freezing to over 300°C (Desbruyères et al., 2006).

While these adaptations are specific to vent habitats, the nutrient plumes emitted by vents can benefit pelagic organisms, including coccolithophores, that do not inhabit vent ecosystems directly.

Scientific and Conservation Significance

Hydrothermal vents are sites of geological and biological interest and hold significant implications for understanding the natural fertilisation of marine ecosystems. The trace metals they release support primary producers such as coccolithophores, influencing carbon cycling, sedimentation, and ecosystem dynamics. However, these systems face growing threats from deep-sea mining activities, which could disrupt nutrient fluxes and impact coccolithophore populations (Van Dover et al., 2018).

Research into the interactions between hydrothermal vents and calcareous nannoplankton provides critical insights into the balance between natural processes and human activities. By investigating the fertilisation potential of Atlantic hydrothermal vents, this study aims to contribute to sustainable resource management and preserve deep-sea ecosystems.

1.3 Blue Mining

The Blue Mining initiative is a European research project dedicated to developing sustainable technologies for deep-sea mineral resource exploration and extraction. The initiative aims to enhance the technological capabilities required for discovering, assessing, and exploiting deep-sea mineral deposits, particularly seafloor massive sulfide (SMS) deposits at depths of up to 6,000 meters (Periodic2 Summary, 2023). The project addressed Europe's growing demand for strategic metals while minimising environmental impact and supporting responsible resource extraction (Hoagland et al., 2010).

The depletion of terrestrial reserves has increased interest in deep-sea hydrothermal vent systems, particularly those in the Atlantic Ocean, as they contain rich mineral deposits (Petersen et al., 2016). These vents discharge nutrient-rich hydrothermal plumes, releasing trace metals such as iron, manganese, and zinc, influencing marine ecosystem productivity, including calcareous nannoplankton communities. This chapter explores how Blue Mining's activities interact with the ecological functions of hydrothermal vents and their impact on marine microorganisms.

Technological Innovations in Blue Mining

The Blue Mining initiative advances deep-sea exploration and resource extraction through cutting-edge technologies designed to minimise ecological disruption while improving efficiency. These include:

- Resource Mapping and Assessment:
  Advanced self-potential sensors and near-bottom seismic systems allow for the precise identification of mineral-rich hydrothermal sites. These tools create detailed imaging of vent plumes and surrounding sediment layers, essential for understanding the distribution of SMS deposits and associated nutrients (Petersen et al., 2016).
- Sediment and Plume Analysis:
  Technologies such as active-source electromagnetic systems and remote sensing devices monitor hydrothermal plumes. These tools help quantify trace metal dispersion, particularly iron, which is critical for evaluating the fertilisation potential of vent systems for primary producers like coccolithophores (Boyd et al., 2000).
- Sustainable Mining Infrastructure:
  Innovative riser systems and ship-to-ship transfer technologies are designed to extract and transport SMS deposits while minimising environmental impact. These systems include sediment containment mechanisms to reduce metal dispersion in the water column, helping preserve nannoplankton communities (Milinovic et al., 2020).
- Real-Time Environmental Monitoring:
  Automated environmental monitoring systems track sediment plumes, nutrient dispersal, and biodiversity changes in active mining areas. This data helps implement adaptive management

strategies, ensuring that mining activities do not excessively disrupt the fertilization effects of hydrothermal vent plumes (Dutrieux et al., 2023).

Relevance to Calcareous Nannoplankton

Calcareous nannoplankton, particularly coccolithophores, play a crucial role in marine biogeochemical cycles and are highly sensitive to environmental changes. These microorganisms rely on trace metals, such as iron, abundant in hydrothermal vent plumes, to sustain their growth and calcification processes (Boyd et al., 2000). Their response to hydrothermal nutrient input can be explored through:

- Enhanced Primary Production:

  The release of iron and other trace metals in hydrothermal vent plumes can stimulate coccolithophore growth, particularly in nutrient-poor regions of the Atlantic Ocean. This increase in primary productivity may lead to higher calcification rates and influence the global carbon cycle (Guerreiro et al., 2024).
- Changes in Species Composition:

  Hydrothermal vent-derived nutrient enrichment may favor opportunistic coccolithophore species, shifting community structures. Similar changes have been observed following Saharan dust deposition, which supplies iron and other micronutrients, leading to blooms of Emiliania huxleyi and Gephyrocapsa oceanica (Guerreiro et al., 2024).
- Paleoceanographic Significance:

  Long-term variations in coccolithophore abundance and species composition caused by hydrothermal activity can leave distinct geochemical signatures in marine sediments. These biogenic sediment records help reconstruct past oceanographic conditions and provide insights into natural fertilisation effects in marine ecosystems (Bown, 1998).

Economic and Ecological Balance

The economic potential of deep-sea mining is significant, but so are the ecological risks. Mining activities near hydrothermal vents may alter nutrient fluxes and disrupt the fertilisation effects of vent plumes on marine ecosystems. The key challenges include:

- Impact on Vent Ecosystems:

  Mining near hydrothermal vents may disturb vent structures, altering the flow of nutrient-rich plumes and reducing the availability of trace metals essential for coccolithophores and other primary producers (Scott & Binns, 1978).
- Sediment Plume Dispersion:

  Mining operations generate sediment plumes that may spread beyond extraction sites, altering nutrient concentrations and disrupting trace metal availability (Milinovic et al., 2020).
- Biodiversity and Ecosystem Resilience:

Hydrothermal vent ecosystems are among the most biodiverse deep-sea habitats. Their loss or degradation could cascade through marine food webs, affecting nannoplankton populations reliant on vent-derived nutrients (Van Dover, 2011).

Sustainability in Blue Mining

The Blue Mining initiative incorporates sustainability strategies to minimise environmental impact while ensuring responsible resource extraction. Key approaches include:

- Precautionary Environmental Assessments:
  Comprehensive environmental impact assessments evaluate the potential effects of mining on nutrient fluxes, coccolithophore populations, and sedimentation patterns (Periodic2 Summary, 2023).
- Adaptive Management:
  Real-time monitoring allows for dynamic operational adjustments, minimising sediment dispersal and preserving nutrient fluxes from vent plumes (Dutrieux et al., 2023).
- Restoration Efforts:
  Although the complete restoration of vent ecosystems is challenging, research into habitat recovery focuses on reestablishing nutrient cycling and supporting coccolithophore productivity.
- Stakeholder Collaboration:
  Blue Mining works with scientists, policymakers, and conservation groups to align deep-sea mining practices with global sustainability goals (Hoagland et al., 2010).

Integrating technological innovation with ecological preservation, the Blue Mining initiative highlights the intricate connections between resource extraction, nutrient cycling, and marine ecosystem dynamics. Ensuring a balance between economic benefits and environmental stewardship is critical for the sustainable use of deep-sea resources and the protection of hydrothermal vent functions.

2. Material and Methods

This study investigates the influence of hydrothermal activity on calcareous nannoplankton by analysing sediment cores collected at varying distances from hydrothermal vents. These cores, positioned proximally, intermediately, and distally from the vents, offer an opportunity to examine how nannoplankton diversity, abundance, and community structure respond to mineral-rich environments. By analysing sediment samples from various depths, the research aims to reveal patterns in nannoplankton assemblages that shed light on the ecological impact of hydrothermal venting on marine ecosystems.

Sample Collection and Provenance

The sediment cores analysed were sourced from the Blue Mining: Breakthrough Solutions for the Sustainable Exploration and Extraction of Deep-Sea Mineral Resources project. These cores were collected near hydrothermal vent systems south of the Azores Archipelago in the Trans-Atlantic Geotraverse (TAG) zone (26°N) along the Mid-Atlantic Ridge (Figure 1; 2). This region is known for its active hydrothermal activity and seafloor massive sulfide (SMS) deposits (Hannington et al., 2011).

Four sediment cores were selected for this study, representing a range of distances from hydrothermal vents:

- M 138 52 GC (proximal sample) (Figure 11)
- M 127 756 GC and M 127 682 GC (intermediate samples) (Figure 13)
- M 127 711 GC (distal sample) (Figure 12)

The cores were retrieved at depths ranging from 2130 to 3600 meters and varied in length from 116 to 300 cm. The table below summarises the core locations and specifications:

Core	Water Depth (m)	Core Length (cm)	Latitude	Longitude
M 138 52 GC	3500 - 3600	190	26°09.471'N	44°49.306'W
M 127 756 GC	3434	116	26°10.422'N	44°48.318'W
M 127 682 GC	3445	281	26°10.243'N	44°48.706'W
M 127 711 GC	2130	300	26°05.485'N	44°38.770'W

Table 1: Core locations and specifications

Samples were collected from various depths within each core to capture vertical variability in sediment composition and nannoplankton distribution.

Figure 1: Geographic location of the hydrothermal field south of the Azores Archipelago, where samples and cores were collected

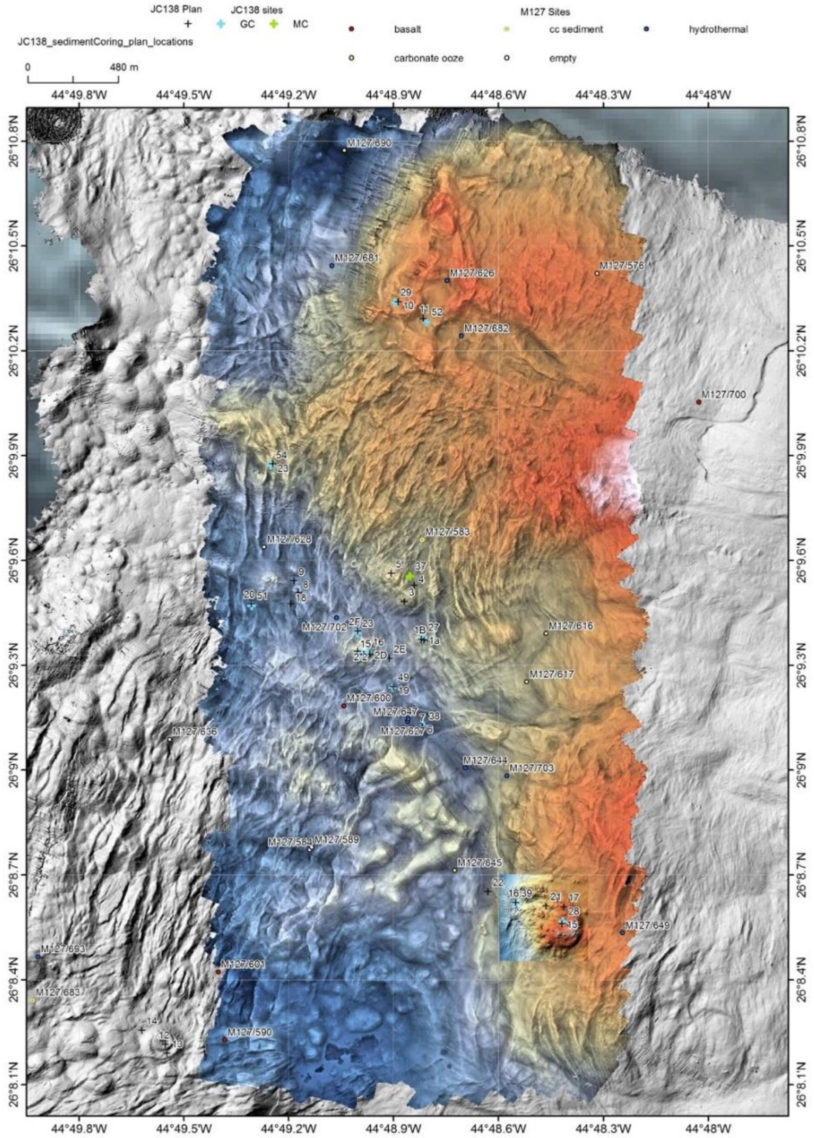

Figure 2: Core locations

Sampling Procedures

Sampling was conducted during research cruises targeting hydrothermal vent systems in the TAG zone along the Mid-Atlantic Ridge. Sediment samples were taken at intervals from the surface and multiple depths within each core (see Appendix I) to investigate vertical variation in calcareous nannoplankton assemblages. The sampled depths were as follows:

- Core JC 138/52 GC: 5 cm, 23 cm, 77 cm
- Core M127/756 GC: 10 cm, 20 cm, 40 cm, 60 cm, 80 cm
- Core M127/682 GC: 10 cm, 20 cm, 45 cm, 78 cm
- Core M127/711 GC: 0 cm, 33 cm, 60 cm, 85 cm

These sampling depths were chosen to ensure adequate representation of vertical changes in sediment composition, capturing potential variability in nannoplankton assemblages caused by environmental and hydrothermal influences.

Slide Preparation Techniques

Random Settling Method

The random settling method, as described by Flores and Sierro (1997), was employed to prepare quantitative slides for microscope analysis. This method ensures uniform distribution of sediment particles on slides, minimising bias and allowing for consistent microscopic analysis:

Preparation Steps:

- Sediment Drying: Sediment samples were dried in an oven to remove moisture.
- Weighing: Approximately 0.2 g of sediment was weighed using a high-precision balance (four decimal places).
- Buffer Solution: A 10 ml buffer solution was prepared with distilled water containing $NaHCO_3$ and Na_2CO_3 to stabilise pH and prevent dissolution of calcareous nannofossils.
- Ultrasonic Mixing: Sediment was suspended in the buffer solution and subjected to ultrasonic mixing for 15 minutes to ensure homogeneity.
- Slide Preparation: A 200 µl aliquot of the suspension was pipetted into a Petri dish containing a glass slide. The suspension was allowed to settle for 24 hours.
- Drying: After removing the supernatant, the slides were dried, mounted with synthetic balsam, and covered with a coverslip. They were then cured for 24 hours on a thermal plate before microscopic analysis.

Buffer Solution Composition

The buffer solution was prepared following established protocols (Guerreiro et al., 2005):

- $NaHCO_3$ (sodium bicarbonate): 0.2000 g

- Na_2CO_3 (sodium carbonate): 0.1500 g
- Distilled water: 1000 ml

This solution stabilised the suspension and prevented calcareous nannofossil dissolution during preparation.

Microscopic Analysis

Prepared slides were analysed using an Olympus BX polarising microscope equipped with:

- Objective: x100 oil immersion
- Eyepiece: x15 with a micrometric reticle
- Camera: Olympus DP21

Slides were examined under x1250 magnification. Taxa were identified following the taxonomy provided by Nannotax3 (Young et al., 2021), and nannoplankton counts were recorded for each sample. Abundance was calculated as the number of individuals per gram of sediment using the following formula:

$$\text{Nannofossil Abundance} = \frac{\text{Number of Individuals Counted} \times \text{Slide Area}}{\text{Area Analyzed} \times \text{Sample Weight}}$$

This method enabled quantitative assessment of nannoplankton diversity and abundance across cores and depths.

Analytical Methods

The collected data analysed vertical and spatial variations in calcareous nannoplankton assemblages. Statistical analyses included:

- Boxplots: To visualise trends in nannoplankton abundance across depths.
- Diversity Indices: Calculated to explore changes in community structure.

Equipment Used

- Microscope: Olympus BX Polarizing Microscope
- Camera: Olympus DP21
- Objective: x100 Oil Immersion
- Eyepiece: x15 with Micrometric Reticle
- Additional Tools: Ultrasonic Bath, Analytical Balance, Micropipette, Thermal Plate
- Data Visualization

To identify patterns in nannoplankton distribution, boxplots were created to illustrate the vertical variability in abundance and diversity. These plots provided insights into how hydrothermal vent proximity influenced nannoplankton communities.

3. Results

This study identified the following 28 nannolith species (see Appendix II with images of some of the species):

Braarudosphaera bigelowii
Calcidiscus leptoporus
Calciosolenia brasiliensis
Ceratolithus cristatus
Coccolithus pelagicus azorinus
Coccolithus pelagicus braarudii
Discosphaera tubifera
Emiliania huxleyi
Florisphera profunda
Gephyrocapsa caribbeanica
Gephyrocapsa ericsonii
Gephyrocapsa muellerae
Gephyrocapsa oceanica
Helicosphaera carteri
Helicosphaera wallichii
Oolithotus fragilis cavum
Pontosphaera japonica
Pontosphaera multipora
Rhabdosphaera clavigera var. clavigera
Rhabdosphaera clavigera var. stylifera
Rhabdosphaera sp.
Scyphosphaera apsteinii
Syracosphera sp.
Syracosphera pulchra
Syracosphaera mediterranea binodata
Thoracosphaera spp.
Umbellosphaera tenuis
Umbilicosphaera sibogae-foliosa

The analysis was conducted based on the individual counts of these species, allowing for an accurate assessment of their abundance and distribution across different samples (see Tables on Appendix III). Abundances were assessed in two main dimensions: absolute values (nannoliths per gram - Nngr^{-1}) and relative percentages (%). The plot of these results as box plots provide a comprehensive view of the distributions, variabilities, and dominances of different nannolith species under various conditions or contexts.

The box plots analysing absolute abundance (Nn gr^{-1}) (see Appendix IV) reveal significant variability among the studied species, reflecting distribution patterns and potential environmental influences.

Braarudosphaera bigelowii (Figure IV-22) exhibited high concentrations in some samples, demonstrating substantial heterogeneity in absolute values. This pattern suggests an uneven distribution, likely influenced by local environmental factors such as nutrient availability, temperature, or salinity. Peaks in abundance indicate that this species may experience sporadic proliferation under favourable conditions, potentially indicating specific ecological events.

In contrast, *Emiliania huxleyi* (Figure IV-8) displayed a far more uniform absolute abundance distribution. The observed values indicate a narrower range of variation across samples, suggesting this species possesses greater resilience or adaptability to varying environmental conditions. This pattern aligns with its status as an ecologically generalist species capable of colonising various habitats.

Gephyrocapsa ericsonii and *Gephyrocapsa muellerae* exhibited similar patterns of absolute aabundance, characterised by pronounced peaks in certain samples and minimal values in others. This behaviour indicates that these species might respond to specific environmental changes, seasonal temperature fluctuations, or nutrient availability fluctuations.

Less frequent species, such as *Oolithotus fragilis* cavum and *Pontosphaera spp.*, demonstrated consistently low concentrations across all analysed samples. This pattern suggests a limited occurrence of these species within the studied environment, potentially due to lower competitiveness or a preference for more specialised environmental conditions.

Relative Percentages of Species

The analysis of species' relative percentages highlighted significant differences in the composition of nannoliths within each sample. These data complement the absolute abundance results, providing more nuanced insights into relative dominance and the contribution of each species to the community. Box plots of the relative percentages are presented in Appendix V.

Emiliania huxleyi dominated the relative composition in most samples, consistently exhibiting high percentages compared to other species. This dominance underscores its role as one of the most ecologically significant species in the studied system. The relative stability of its percentages suggests that *E. huxleyi* plays a central role in the dynamics of nannolith communities, potentially forming the base of local food chains.

Species such as *Florisphera profunda* and *Discosphaera tubifera* presented more modest but stable percentages. This behaviour may indicate that these species occupy secondary ecological niches, contributing consistently, albeit less prominently, to overall diversity.

In contrast, *Coccolithus pelagicus azorinus* and *Coccolithus pelagicus braarudii* exhibited more pronounced fluctuations in their relative composition. These variations may be linked to localised environmental changes or competitive interactions within the community.

Smaller groups, including *Syracosphaera spp.* and *Thoracosphaera spp.*, consistently display low percentages across all samples. This trend indicates that these groups play a minor role in the community composition, possibly reflecting their lower absolute abundance or restrictions to specific environmental conditions.

Overall Comparison and Notable Observations

The comparison of absolute abundance and relative percentage box plots provides a detailed and enriched perspective of the structure of nannolith communities. Differences in species variability are striking. While *Emiliania huxleyi* displays lower variability, other species, such as *Braarudosphaera bigelowii*, exhibit extreme values indicative of sporadic proliferation events.

Additionally, the data reveals that relative composition offers a complementary perspective to absolute abundance, emphasising the relative dominance of certain species even when their absolute concentrations are low. For instance, species such as *Florisphera profunda* maintain a stable contribution to the community despite their lower absolute abundance.

This combination of analyses enhances the understanding of ecological dynamics and interactions among different nannolith groups in the studied environment. Furthermore, these results provide a foundation for future investigations into the environmental factors regulating the composition and distribution of these communities.

4. Discussion

The findings of this study provide crucial insights into the influence of hydrothermal vent activity on nannoplankton communities in the TAG area along the Mid-Atlantic Ridge. By analysing sediment cores collected at varying distances from hydrothermal vents, this research offers a nuanced understanding of how nannoplankton abundance, diversity, and ecological composition respond to mineral-rich environments. This discussion connects the results to the study's objectives and explores their implications for deep-sea mining and paleoceanographic studies.

Influence of Hydrothermal Vents on Nannoplankton Distribution

The updated results reinforce the localised impact of hydrothermal vents on nannoplankton communities. The spatial variations in *Florisphera profunda, Emiliania huxleyi, Calcidiscus leptoporus*, and *Gephyrocapsa oceanica* illustrate how vent-associated environmental factors, such as nutrient enrichment and altered water chemistry, shape nannoplankton distribution patterns (McIntyre & Bé, 1967; Roth, 1994).

Cores proximal to the hydrothermal vent (e.g., JC 138/52 GC) exhibited elevated concentrations of *Florisphera profunda*, a deep-dwelling species associated with nutrient-rich, low-light conditions. These results align with studies suggesting that hydrothermal activity enhances the proliferation of such species by supplying essential minerals and nutrients (Molfino & McIntyre, 1990; German & Von Damm, 2003). The persistence of F. profunda across deeper sediment layers, combined with high variability in abundance, suggests fluctuating hydrothermal activity over time, influencing biogeochemical cycles in the region (Baumann et al., 2005).

However, despite the expected increase in abundance near hydrothermal sources due to higher nutrient availability, the intermediate cores (e.g., M 127/45 GC) exhibited a more significant overall number of individuals than the proximal cores. This pattern suggests that while hydrothermal vents provide essential nutrients, they also release high concentrations of potentially harmful elements, such as heavy metals (e.g., Fe, Cu, Zn, Pb) and toxic compounds (e.g., hydrogen sulfide - H_2S), which can negatively impact nannoplankton populations (Tunnicliffe et al., 1986; Koschinsky et al., 2003). The direct exposure to these elements near the vent may result in localised stress conditions, reducing species abundance despite nutrient enrichment.

In contrast, distal cores (e.g., M 127/711 GC) showed a clear dominance of *Emiliania huxleyi*, a surface-dwelling species adapted to oligotrophic conditions. The relative consistency of *E. huxleyi* abundance in these cores highlights the diminishing influence of hydrothermal vents with increasing distance, transitioning to environments characteristic of open-ocean systems. Intermediate species, such as *Calcidiscus leptoporus,* demonstrated moderate abundances across varying distances, indicating their adaptability to less extreme conditions (Winter et al., 1994).

Vertical Variation and Environmental Conditions Over Time

The vertical profiles of nannoplankton abundance and diversity within sediment cores provide valuable insights into historical environmental conditions. Deeper layers revealed higher abundances of *Florisphera profunda,* indicative of periods of heightened hydrothermal activity (McIntyre & Bé, 1967). These findings underscore the role of hydrothermal vents in creating nutrient-enriched conditions favorable to deep-dwelling species (Roth, 1994).

Conversely, surface layers were dominated *by Emiliania huxleyi*, reflecting recent oligotrophic surface water conditions. Notably, species such as *Gephyrocapsa oceanica* displayed distinct peaks in specific sediment layers, suggesting episodic environmental changes. This stratification emphasises the influence of tectonic and volcanic activity on hydrothermal venting and its ecological impacts over time (German & Von Damm, 2003).

The observed patterns further support the idea that intermediate cores provide the most favorable balance of conditions for nannoplankton proliferation. While hydrothermal vents release essential micronutrients such as iron (Fe) and manganese (Mn), they also emit elevated levels of toxic elements like cadmium (Cd), lead (Pb), and arsenic (As), which can negatively affect planktonic communities (Tunnicliffe et al., 1986; Edmonds & German, 2004). Intermediate zones may represent a transition where nutrient benefits outweigh toxicity, increasing overall abundances.

Implications for Deep-Sea Mining

The results underline the ecological sensitivity of hydrothermal vent-associated environments. The dominance of *Florisphera profunda* in vent-influenced sediments highlights the importance of nutrient flows sustained by hydrothermal activity. Deep-sea mining operations targeting seafloor massive sulfide (SMS) deposits could disrupt these ecosystems, potentially leading to the loss of deep-dwelling species and altering community structures (Van Dover, 2000; Blue Mining Project, 2016).

Moreover, disturbances to sediment layers could affect the balance between surface and deep-dwelling species, impacting biodiversity and ecosystem functionality. Given the observed impact of toxic element concentrations near hydrothermal vents, further research is needed to assess how mining activities could exacerbate these stressors. These findings emphasise the need for rigorous environmental impact assessments and the development of sustainable frameworks to mitigate mining-related impacts on vent-associated ecosystems (German & Von Damm, 2003; Baumann et al., 2005).

Calcareous nannoplankton as Paleoceanographic Proxies

This study's spatial and vertical distributions of nannoplankton reinforce their utility as proxies for reconstructing past oceanic conditions. Variations in species such as *Florisphera profunda* and

Emiliania huxleyi reflect changes in hydrothermal activity, nutrient availability, and water chemistry over time (Winter et al., 1994; Baumann et al., 2005).

For example, the observed shift from deep-dwelling to surface-dwelling species in sediment cores provides a valuable record of paleoceanographic transitions. The fluctuating abundances of F. profunda in deeper layers further support the notion that hydrothermal activity has varied over time, influencing biogeochemical cycles and primary marine production. The recognition that intermediate zones sustain the highest nannoplankton abundance due to optimal nutrient-toxicity balance is also relevant for interpreting past hydrothermal influences on marine ecosystems.

By integrating these findings, this study contributes to broader efforts to understand the Mid-Atlantic Ridge region's ocean circulation patterns and biogeochemical cycles, reinforcing the role of hydrothermal vent systems as key regulators of deep-sea biodiversity and carbon cycling.

5. Conclusions

This study has significantly advanced our understanding of the impact of hydrothermal vent activity on nannoplankton communities in the TAG area along the Mid-Atlantic Ridge. By analysing sediment cores collected at varying distances from hydrothermal vents, several key findings have emerged:

Species Distribution and Vent Proximity

Florisphera profunda, a deep-dwelling species, dominated sediment cores near the hydrothermal vent, highlighting the nutrient-rich, low-oxygen environments created by vent activity (Roth, 1994; Molfino & McIntyre, 1990).

Surface-dwelling species such as *Emiliania huxleyi* prevailed in distal cores, reflecting oligotrophic conditions typical of open-ocean systems (Winter et al., 1994).

Interestingly, intermediate cores displayed the highest overall nannoplankton abundances. While hydrothermal vents provide essential nutrients that promote biological productivity, they also release high concentrations of potentially toxic elements such as Fe, Cu, Zn, Pb, and hydrogen sulfide (H_2S) (Tunnicliffe et al., 1986; Koschinsky et al., 2003). These elements can create stressful conditions near the vent, limiting nannoplankton proliferation. The intermediate zones may represent a transition where nutrient benefits outweigh toxicity, leading to higher observed abundances.

Vertical and Temporal Variations

Deeper sediment layers showed higher abundances of *Florisphera profunda*, reflecting periods of intensified hydrothermal activity (McIntyre & Bé, 1967).

Emiliania huxleyi dominated surface layers, indicative of recent oligotrophic conditions (Baumann et al., 2005).

The variations in *Gephyrocapsa oceanica* and *Calcidiscus leptoporus* across sediment layers suggest episodic environmental shifts, likely linked to fluctuations in hydrothermal vent activity.

Diversity and Environmental Sensitivity

Species diversity increased with distance from the vent, with vent-adjacent environments supporting more specialised communities.

The unique composition of vent-associated nannoplankton underscores their ecological vulnerability to disturbances, such as those caused by deep-sea mining (Van Dover, 2000).

The presence of toxic hydrothermal emissions likely plays a significant role in shaping nannoplankton distributions, further emphasising the need to consider chemical stressors in future ecological assessments of vent ecosystems.

6. Future Work

Building on the findings of this study, several avenues for future research are recommended:

Expanded Sampling and Analysis

Collect additional sediment cores across a broader geographical range to better understand the spatial extent of hydrothermal vent influence on nannoplankton communities.

Incorporate additional environmental parameters, such as water chemistry, metal concentrations, and temperature profiles, to strengthen the link between vent activity and nannoplankton distribution (German & Von Damm, 2003).

Long-Term Monitoring

Time-series analyses are conducted to observe temporal changes in species composition and abundance, particularly in response to fluctuations in hydrothermal venting activity (McIntyre & Bé, 1967).

Monitor seasonal and interannual variations in hydrothermal emissions to assess their impact on nannoplankton productivity and biodiversity.

Molecular and Genetic Studies

Investigate the genetic adaptations of nannoplankton species to hydrothermal environments to better understand their resilience and ecological roles (Roth, 1994).

Assess whether certain species have evolved mechanisms to tolerate elevated concentrations of toxic metals and sulfide-rich environments.

Impacts of Deep-Sea Mining

Model the potential impacts of sediment disturbance and nutrient disruption caused by mining on nannoplankton communities and broader marine ecosystems.

Develop frameworks for environmental impact assessments to mitigate harm to vent-associated communities (Van Dover, 2000).

Investigate how the removal of hydrothermal deposits could alter the geochemical balance, affecting primary producers and higher trophic levels.

Nannoplankton as Paleoceanographic Proxies

Utilize nannoplankton assemblages to reconstruct historical changes in hydrothermal activity, nutrient availability, and water mass circulation in the Mid-Atlantic Ridge (Baumann et al., 2005).

Investigate how past hydrothermal emissions influenced global climate and ocean productivity through interactions with carbon and sulfur cycles.

Dating and Geochemical Analysis

Perform detailed geochemical analysis of sediment layers to better understand their chemical composition and its relationship to species distribution.

Apply precise dating techniques to sediment cores to establish a chronological framework for changes in hydrothermal activity and their impact on nannoplankton communities (Winter et al., 1994).

Evaluate metal concentrations in different sediment layers to confirm the role of toxic emissions in shaping nannoplankton community structures over time.

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Appendix I

Images of the cores

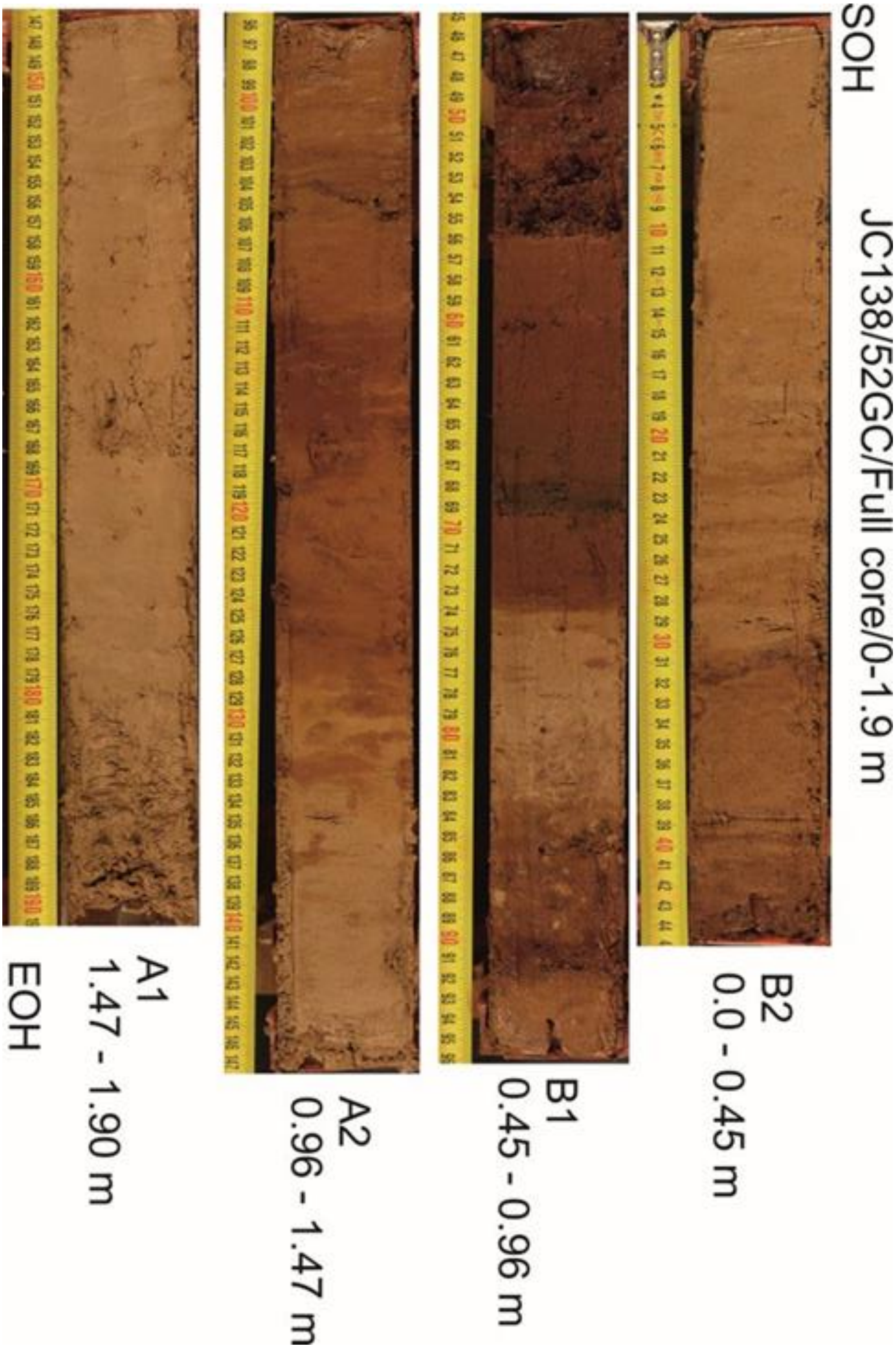


Fig. I-1 Images of the Core JC138/52

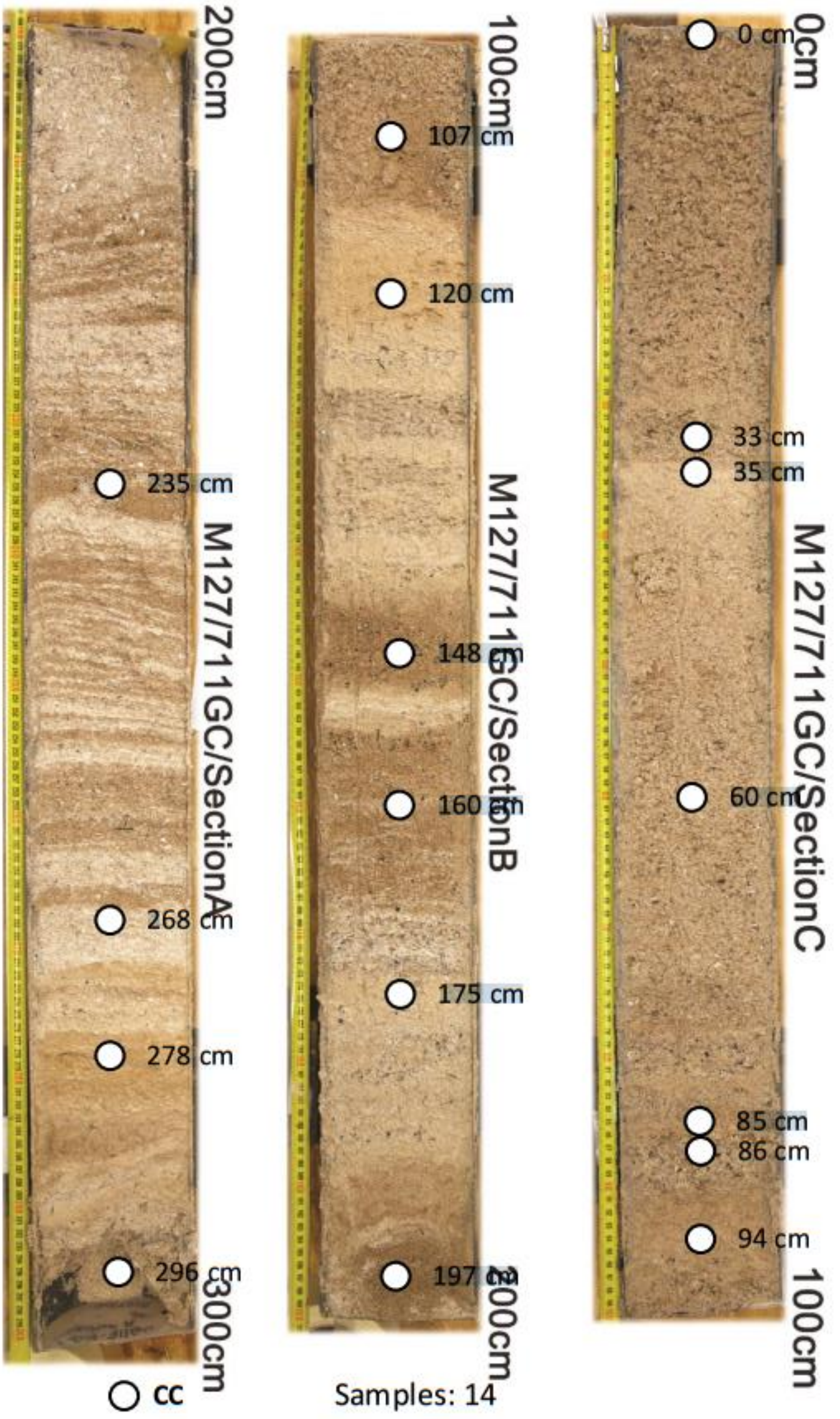


Fig. I-2 Images of the Core M127/711

Fig. I-3 Images of the: Core M127/576

Appendix II

Plates with images of the most representative calcareous nannofossils.

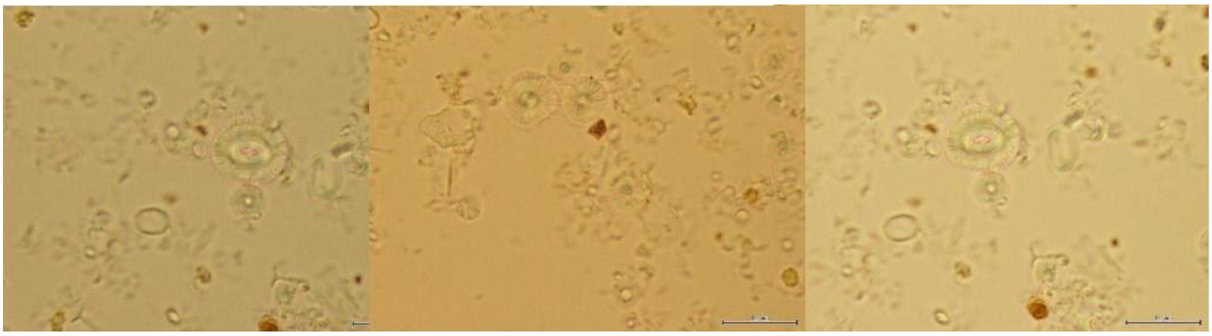


Fig II-1: Coccolithus pelagicus braarudii (Parallel nicols)

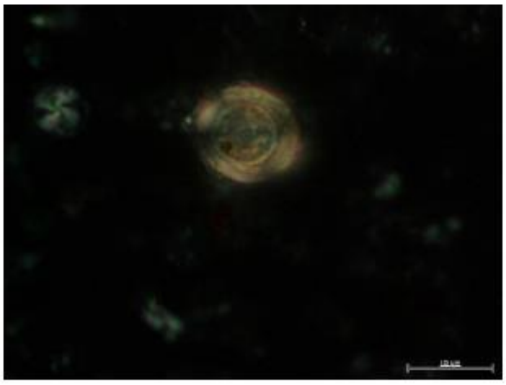


Fig II-2: Coccolithus pelagicus braarudii (Crossed nicols)

Fig II-3: Coccolithus pelagicus azorinus (Parallel nicols)

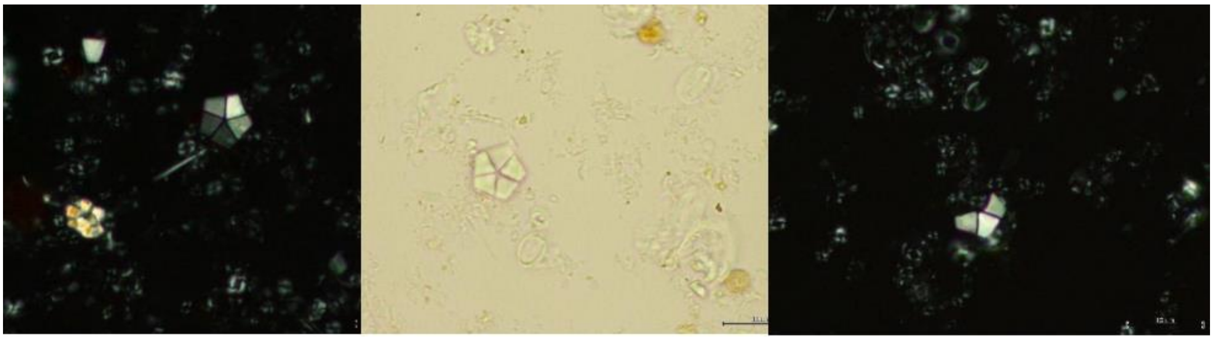


Fig II-4: Braarudosphaera bigelowii (Crossed nicols; Parallel nicols; Crossed nicols)

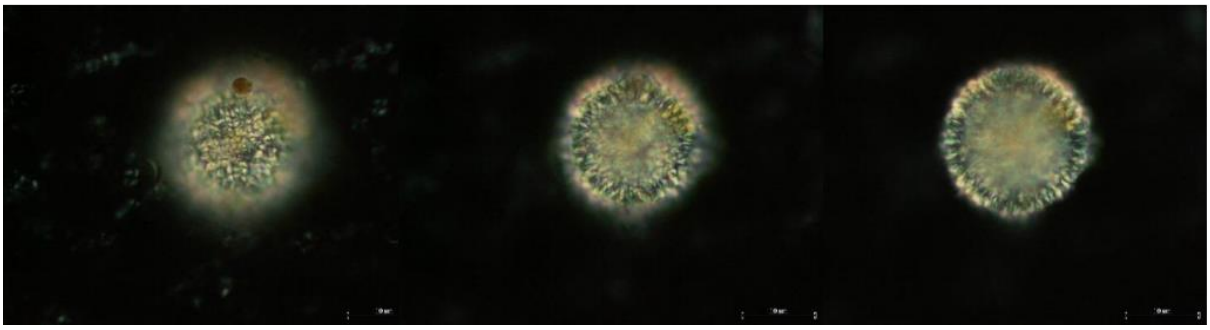


Fig II-5: Thoracosphaera spp. (Crossed nicols)

Fig II-6: Ceratolithus spp. (A - Crossed nicols; B - Parallel nicols; C - Crossed nicols)

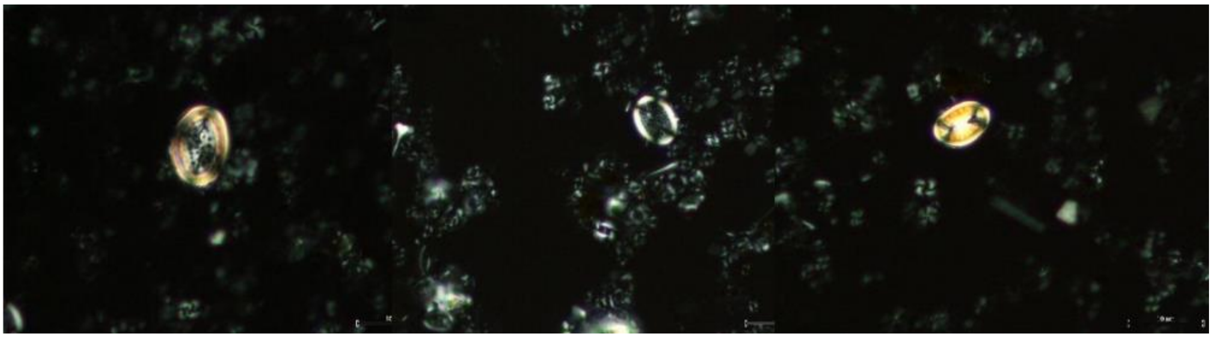


Fig II-7: Pontosphaera spp. (Crossed nicols)

Fig II-8: Scyphosphaera spp. (A - *Crossed nicols; B - Parallel nicols; C - Crossed nicols*)

Appendix III

Tables with the absolute Abundances of the calcareous nannofossils

	Core	Depth (cm)	*Calcidiscus leptoporus*	*Oolithotus fragilis cavum*	*Umbilicosphaera sibogae-foliosa*	*Coccolithus pelagicus braarudii*	*Coccolithus pelagicus azorinus*	*Helicosphaera spp*	*Gephyrocapsa oceanica*	*Gephyrocapsa muellerae*
1	JC 138/52 GC	5	203 270 953	19 671 383	281 956 484	6 557 128	0	104 914 040	177 042 443	360 642 014
2	JC 138/52 GC	23	152 999 642	0	206 549 517	7 649 982	0	260 099 392	221 849 481	856 797 996
4	JC 138/52 GC	77	313 649 267	0	382 499 106	45 899 893	0	99 449 767	237 149 445	810 898 104
5	M127/756 GC	10	413 099 034	15 299 964	305 999 284	7 649 982	15 299 964	53 549 875	168 299 606	405 449 052
6	M127/756 GC	20	642 598 497	45 899 893	266 219 377	36 719 914	0	146 879 657	321 299 249	1 064 877 510
7	M127/756 GC	40	284 579 335	0	578 338 648	45 899 893	0	128 519 699	330 479 227	2 120 575 041
8	M127/756 GC	60	917 997 853	0	862 917 982	73 439 828	0	192 779 549	468 178 905	2 331 714 547
9	M127/756 GC	80	111 471 168	0	190 156 698	19 671 383	0	72 128 403	104 914 040	1 075 368 914
10	M127/682 GC	10	917 997 853	0	908 817 875	18 359 957	0	284 579 335	725 218 304	2 019 595 277
11	M127/682 GC	20	413 099 034	45 899 893	670 138 433	0	9 179 979	137 699 678	1 331 096 887	2 221 554 805
12	M127/682 GC	45	422 279 013	0	495 718 841	27 539 936	9 179 979	275 399 356	1 175 037 252	2 689 733 710
13	M127/682 GC	78	431 458 991	0	449 818 948	55 079 871	0	156 059 635	367 199 141	1 083 237 467
14	M127/711 GC	0	9 179 979	0	36 719 914	0	0	27 539 936	9 179 979	27 539 936
15	M127/711 GC	33	0	45 899 893	9 179 979	0	0	27 539 936	0	36 719 914
16	M127/711 GC	60	0	45 899 893	18 359 957	0	0	18 359 957	18 359 957	73 439 828
17	M127/711 GC	85	18 359 957	91 799 785	45 899 893	9 179 979	0	0	18 359 957	82 619 807

Table III - 1: Absolute abundances (nannoliths per gram)

	Core	Depth (cm)	*Gephyrocapsa spp*	*Pontosphaera sp.*	*Syracosphera pulchra*	*Syracosphera sp.*	*Discosphaera tubifera*	*Umbellosphaera tenuis*	*Rhabdosphaera clavigera*	*Rhabdosphaera sp.*
1	JC 138/52 GC	5	1 514 696 458	19 671 383	59 014 148	177 042 443	72 128 403	177 042 443	124 585 423	6 557 128
2	JC 138/52 GC	23	2 432 694 311	61 199 857	22 949 946	198 899 535	61 199 857	137 699 678	152 999 642	15 299 964
4	JC 138/52 GC	77	2 669 843 757	0	107 099 750	30 599 928	7 649 982	122 399 714	114 749 732	7 649 982
5	M127/756 GC	10	4 000 940 644	15 299 964	183 599 571	15 299 964	114 749 732	198 899 535	168 299 606	0
6	M127/756 GC	20	4 397 209 717	36 719 914	146 879 657	73 439 828	165 239 614	174 419 592	146 879 657	0
7	M127/756 GC	40	2 616 293 882	45 899 893	192 779 549	64 259 850	73 439 828	220 319 485	110 159 742	0
8	M127/756 GC	60	2 671 373 753	9 179 979	275 399 356	73 439 828	128 519 699	302 939 292	137 699 678	0
9	M127/756 GC	80	1 639 281 881	6 557 128	118 028 295	0	26 228 510	45 899 893	85 242 658	13 114 255
10	M127/682 GC	10	5 608 966 884	27 539 936	477 358 884	82 619 807	220 319 485	257 039 399	220 319 485	9 179 979
11	M127/682 GC	20	6 251 565 381	18 359 957	394 739 077	45 899 893	64 259 850	220 319 485	55 079 871	0
12	M127/682 GC	45	4 764 408 859	27 539 936	211 139 506	18 359 957	45 899 893	119 339 721	165 239 614	9 179 979
13	M127/682 GC	78	1 845 175 685	18 359 957	174 419 592	64 259 850	0	110 159 742	82 619 807	0
14	M127/711 GC	0	91 799 785	9 179 979	9 179 979	0	0	0	18 359 957	0
15	M127/711 GC	33	284 579 335	0	27 539 936	0	0	45 899 893	0	0
16	M127/711 GC	60	330 479 227	0	27 539 936	0	0	0	9 179 979	0
17	M127/711 GC	85	275 399 356	0	9 179 979	0	0	9 179 979	0	0

Table III - 2: Absolute abundances (nannoliths per gram)

	Core	Depth (cm)	*Scyphosphaera apsteinii*	*Braarudosphaera bigelowii*	*Thoracosphaera spp.*	*Ceratolithus cristatus*	*Calciosolenia brasiliensis*	*Emiliania huxleyi*	*Florisphera profunda*
1	JC 138/52 GC	5	6 557 128	0	19 671 383	65 571 275	98 356 913	1 324 539 760	3 855 590 984
2	JC 138/52 GC	23	0	0	22 949 946	0	152 999 642	2 486 244 186	8 942 829 088
4	JC 138/52 GC	77	0	0	22 949 946	0	38 249 911	4 375 789 768	7 466 382 540
5	M127/756 GC	10	7 649 982	30 599 928	30 599 928	0	114 749 732	1 055 697 531	6 158 235 599
6	M127/756 GC	20	9 179 979	36 719 914	18 359 957	9 179 979	110 159 742	4 902 108 537	8 546 560 014
7	M127/756 GC	40	9 179 979	0	27 539 936	18 359 957	238 679 442	4 149 350 297	6 637 124 480
8	M127/756 GC	60	18 359 957	0	18 359 957	0	229 499 463	6 930 883 793	5 618 146 862
9	M127/756 GC	80	0	0	6 557 128	0	91 799 785	465 556 054	4 491 632 354
10	M127/682 GC	10	9 179 979	64 259 850	119 339 721	36 719 914	275 399 356	6 233 205 424	15 762 023 142
11	M127/682 GC	20	9 179 979	0	0	0	266 219 377	6 756 464 200	8 500 660 122
12	M127/682 GC	45	27 539 936	0	18 359 957	18 359 957	183 599 571	9 023 918 898	11 245 473 703
13	M127/682 GC	78	0	0	27 539 936	0	119 339 721	2 772 353 517	8 702 619 649
14	M127/711 GC	0	0	9 179 979	0	0	18 359 957	110 159 742	504 898 819
15	M127/711 GC	33	0	18 359 957	0	0	0	137 699 678	688 498 390
16	M127/711 GC	60	0	0	9 179 979	0	0	82 619 807	660 958 454
17	M127/711 GC	85	0	18 359 957	0	0	18 359 957	220 319 485	339 659 206

Table III - 3: Absolute abundances (nannoliths per gram)

Appendix IV

Box Plots of the absolute Abundances (nannoliths per gram) of the calcareous nannofossils

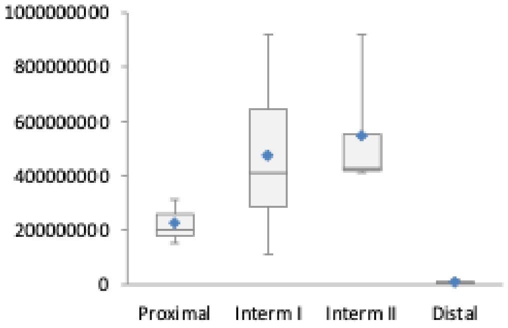


Fig. IV-1: Calcidiscus leptoporus

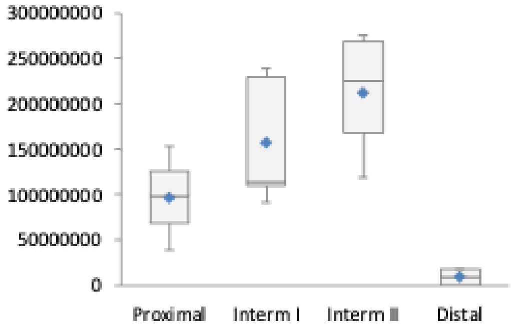


Fig. IV-2: Calciosolenia brasiliensis

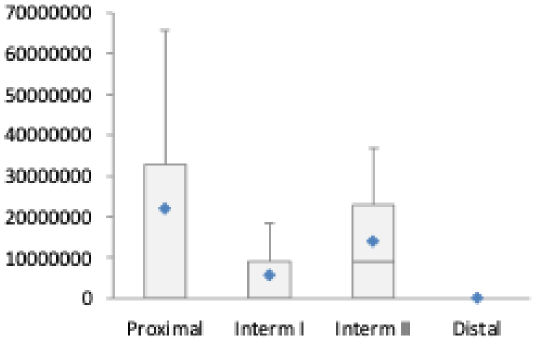
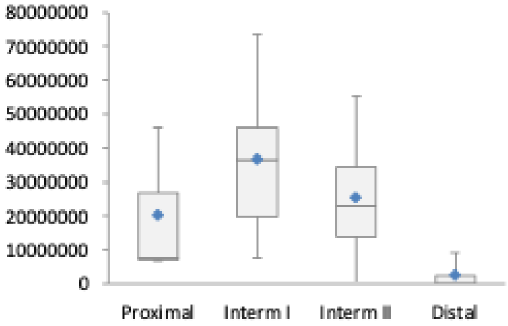


Fig. IV-3: Ceratolithus cristatus



3: Coccolithus pelagicus braarudii

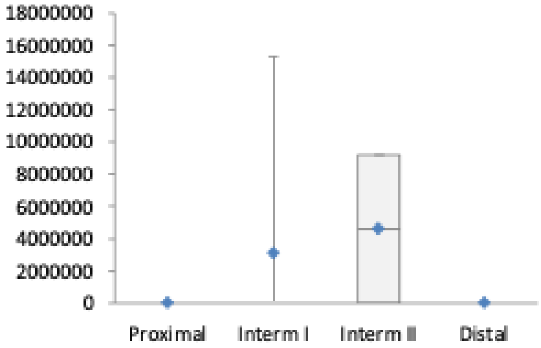


Fig. IV-5: Coccolithus pelagicus azorinus

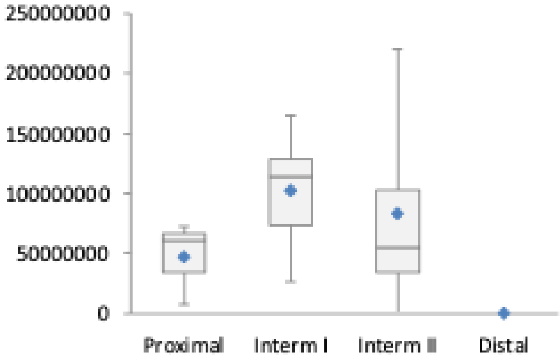
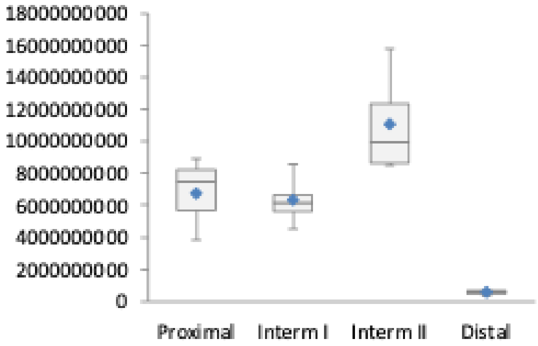


Fig. IV-6: Discosphaera tubifera



4:Florisphera profunda

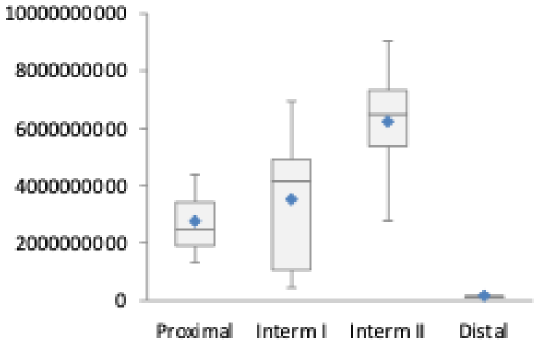


Fig. IV-8: Emiliania huxleyi

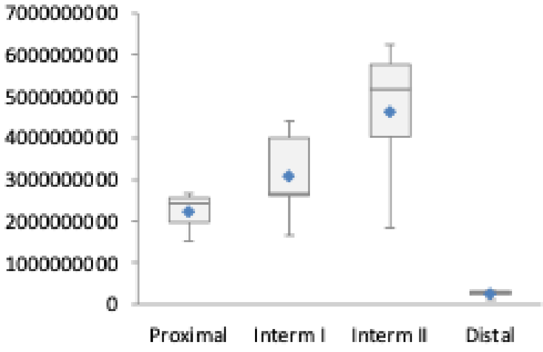


Fig. IV-9: *Gephyrocapsa ericsonii*

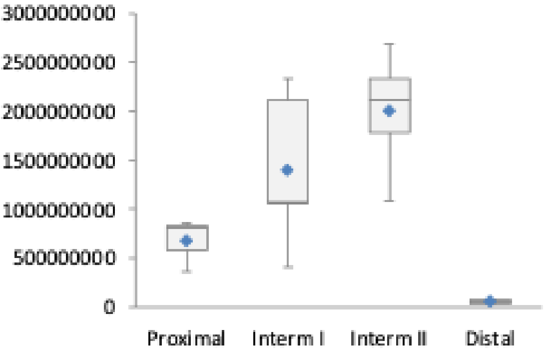


Fig. IV-10: *Gephyrocapsa muellerae*

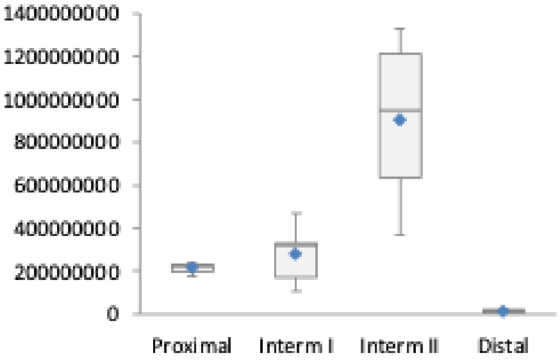
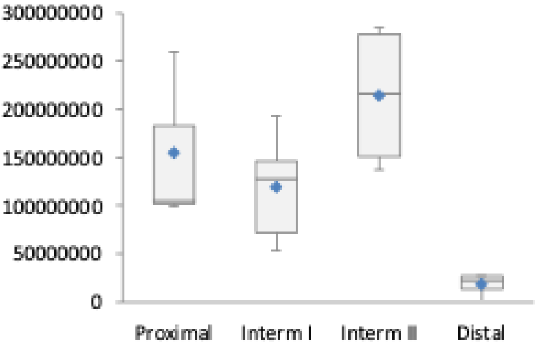


Fig. IV-11: *Gephyrocapsa oceanica*



5: *Helicosphaera spp.*

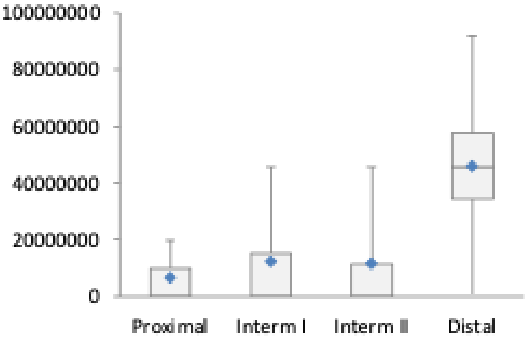


Fig. IV-13: *Oolithotus fragilis cavum*

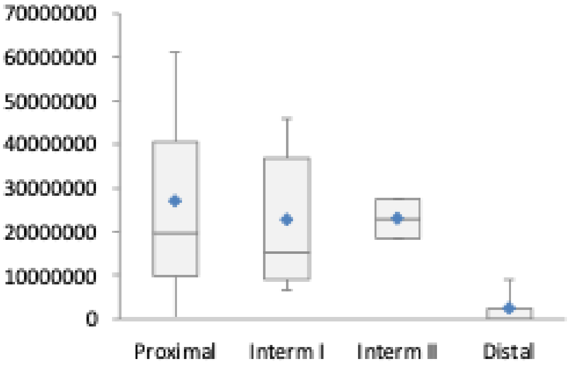


Fig. IV-14: *Pontosphaera spp.*

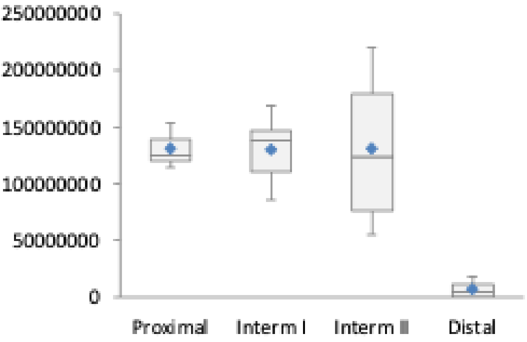


Fig. IV-15: *Rhabdosphaera clavigera*

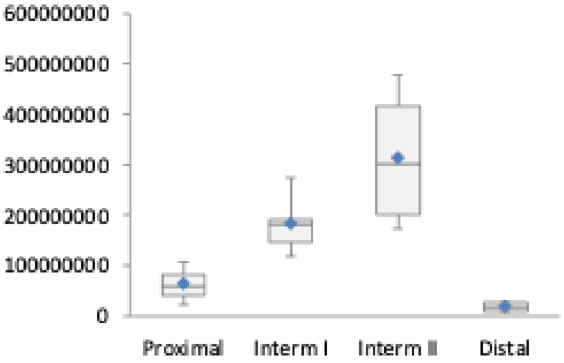
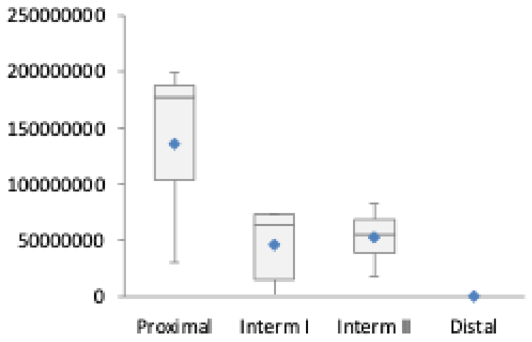


Fig. IV-16: *Syracosphera pulchra*



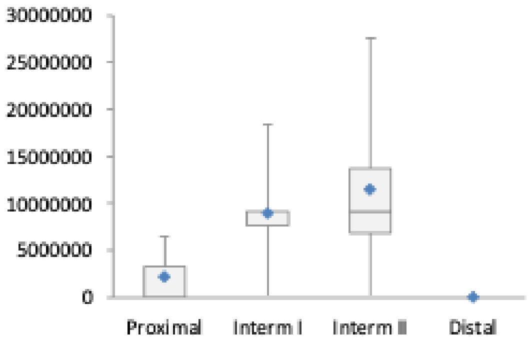
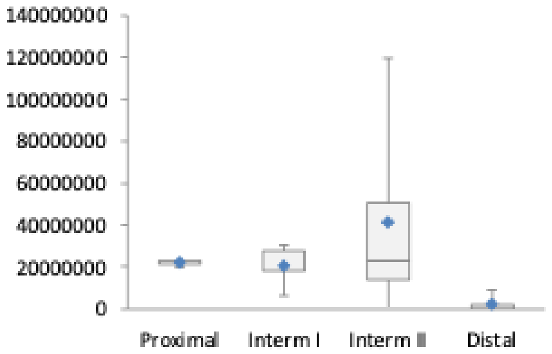


Fig. IV-17: Coronosphaera mediterranea

Fig. IV-18: Scyphosphaera apsteinii



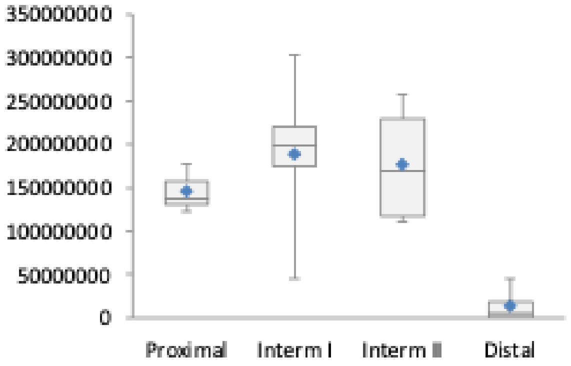
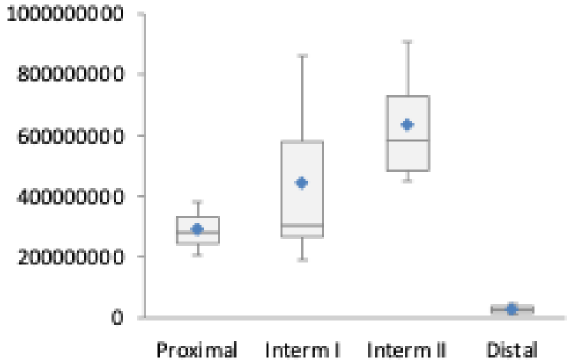


Fig. IV-19: Thoracosphaera spp.

Fig. IV-20: Umbellosphaera tenuis



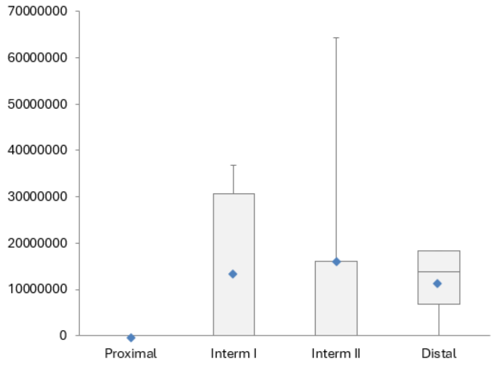


Fig. IV-21: Umbilicosphaera sibogae-foliosa

Fig. IV-22: Braarudosphaera bigelowii

Appendix V

Box Plots of the relative Abundances (percentages) of the calcareous nannofossils

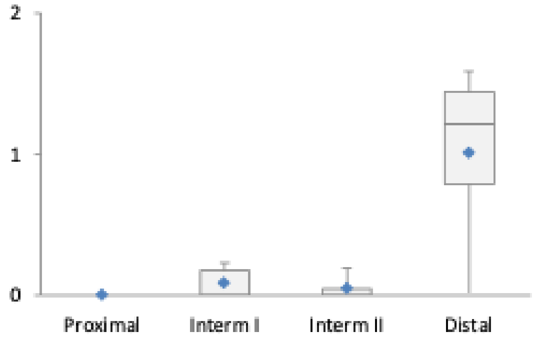


Fig. V-1: Braarudosphaera bigelowii

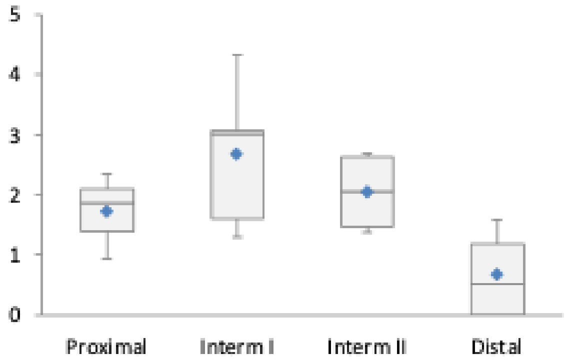
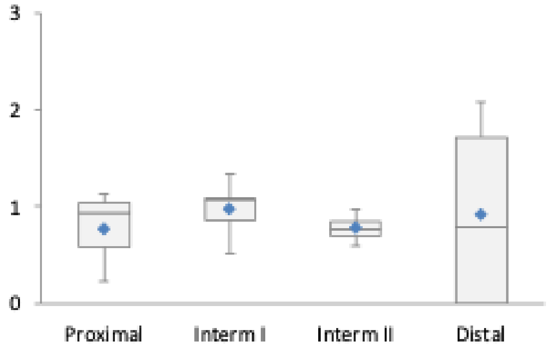


Fig. V-2: Calcidiscus leptoporus



6: Calciosolenia brasiliensis

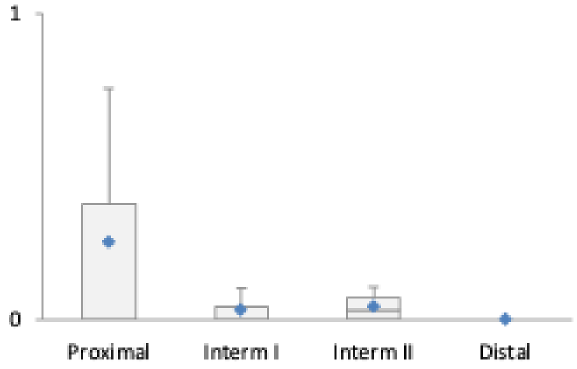


Fig. V-4: Ceratolithus cristatus

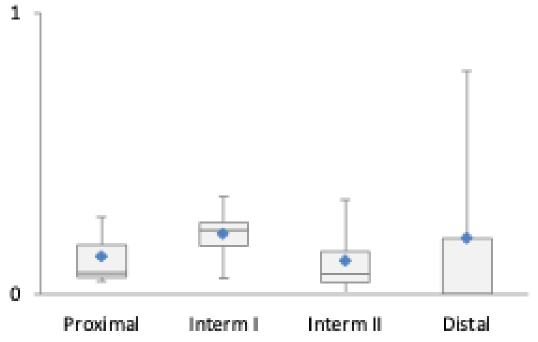


Fig. V-5: Coccolithus pelagicus braarudii

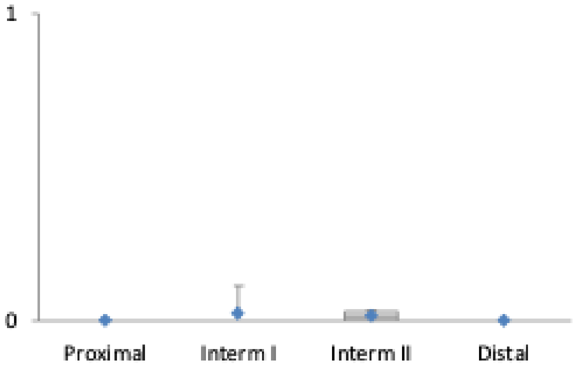


Fig. V-6: Coccolithus pelagicus azorinus

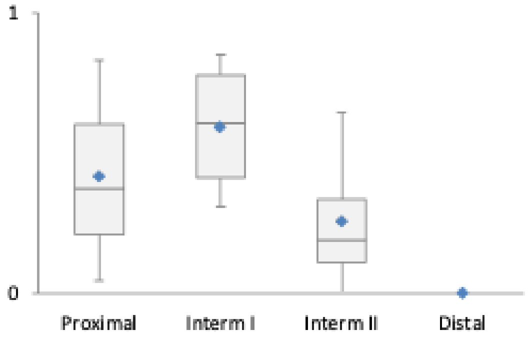


Fig. V-7: Discosphaera tubifera

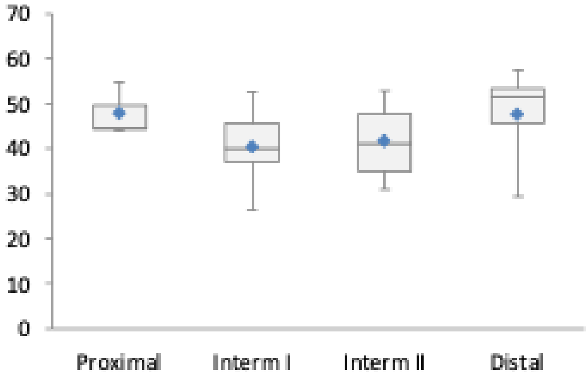


Fig. V-8: Florisphera profunda

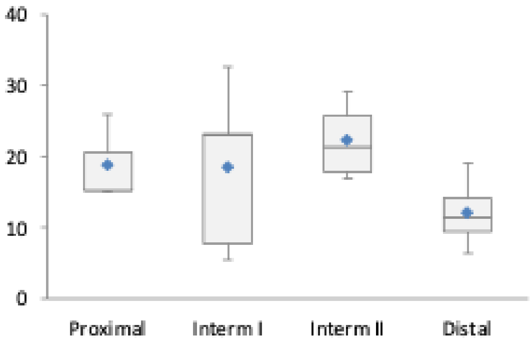


Fig. V-9:Emiliania huxleyi

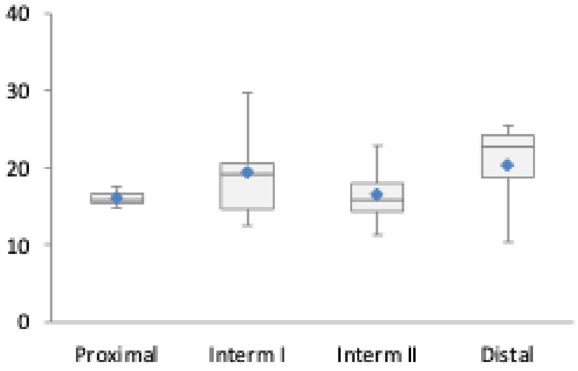


Fig. V-10:Gephyrocapsa ericsonii

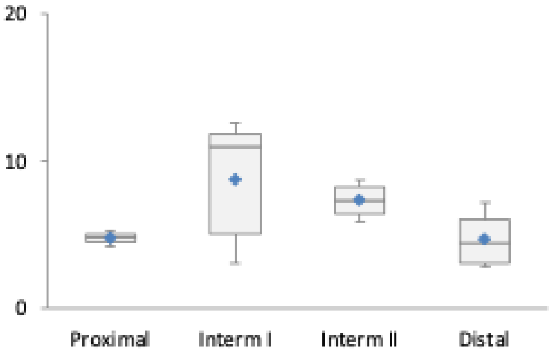


Fig. V-11: Gephyrocapsa muellerae

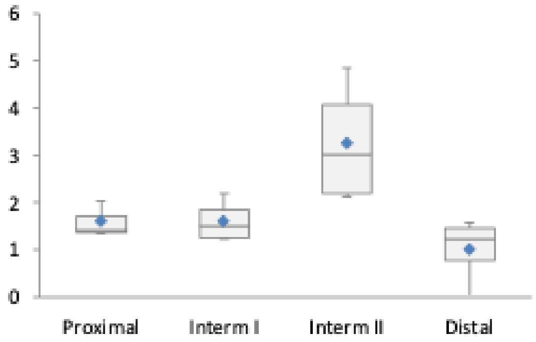


Fig. V-12: Gephyrocapsa oceanica

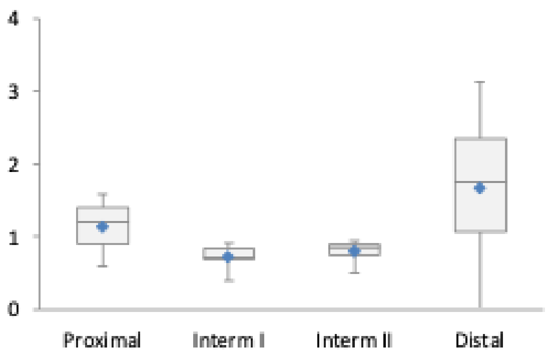


Fig. V-13: *Helicosphaera* spp.

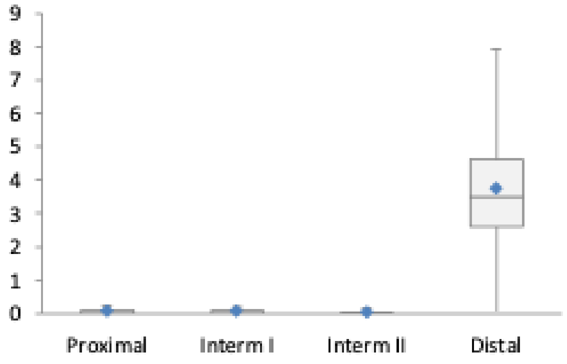


Fig. V-14:*Oolithotus fragilis cavum*

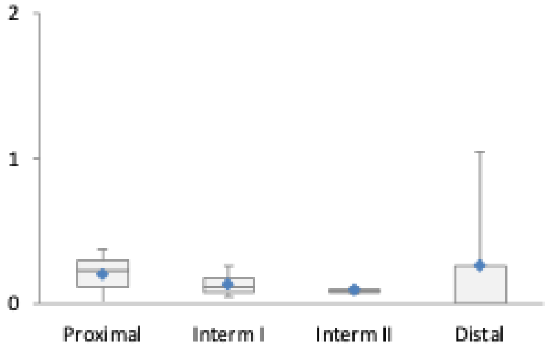


Fig. V-15: *Pontosphaera* spp.

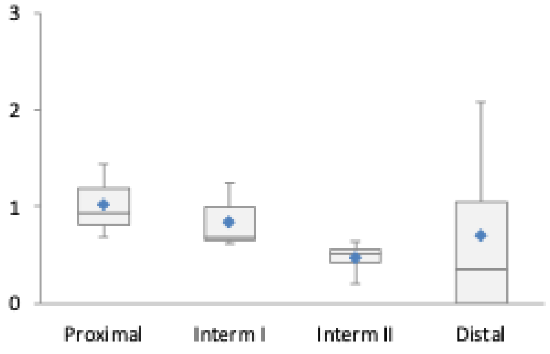


Fig. V-16: *Rhabdosphaera clavigera*

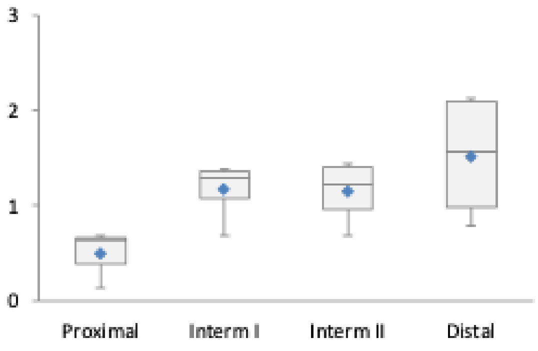


Fig. V-17: *Syracosphera pulchra*

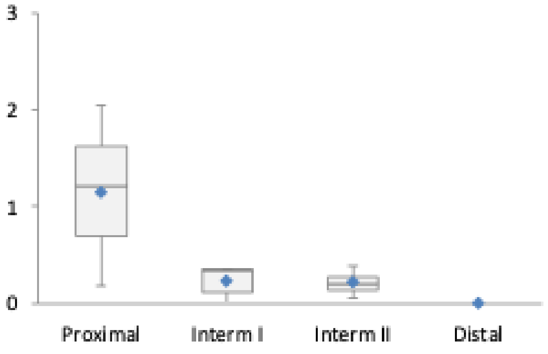


Fig. V-18: *Coronosphaera mediterranea*

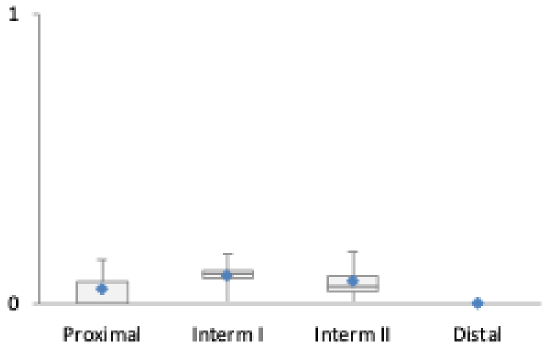


Fig. V-19: Scyphosphaera apsteinii

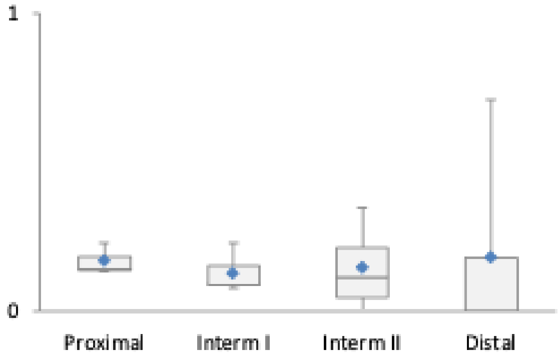


Fig. V-20: Thoracosphaera spp.

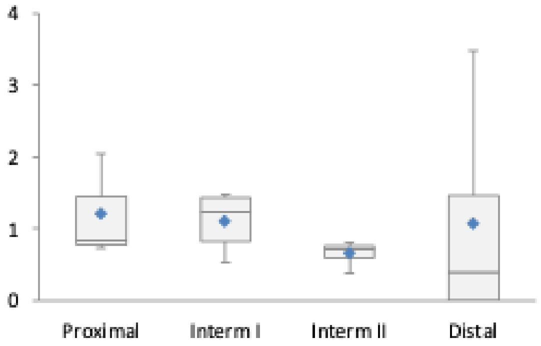


Fig. V-21: Umbellosphaera tenuis foliosa

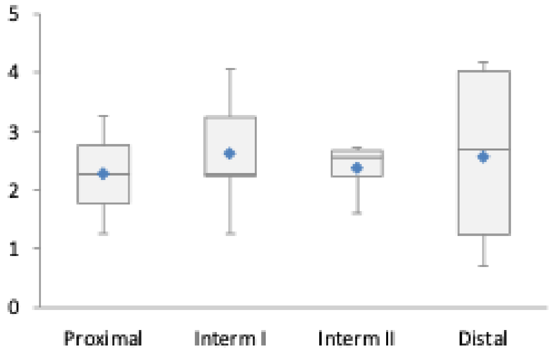


Fig. V-22: Umbilicosphaera sibogae-